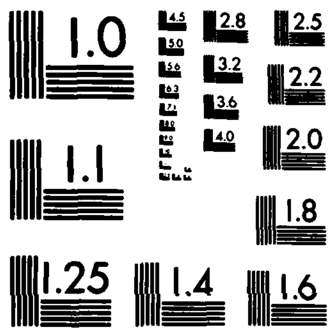
AD-A132 856 TECHNICAL EVALUATION REPORT ON THE FLIGHT MECHANICS PANEL SYMPOSIUM ON GR..(U) ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT NEUILLY.. J WILLIAMS JUN 83 1/1

UNCLASSIFIED AGARD-AR-191 F/G 14/2 NL



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

DTIC
ELECTE
SEP 2 2 1983
S D
A

(2)

AGARD-AR-191

AGARD-AR-191

AD-A132 856

AGARD

ADVISORY GROUP FOR AEROSPACE RESEARCH & DEVELOPMENT

7 RUE ANCELLE 92200 NEUILLY SUR SEINE FRANCE

AGARD ADVISORY REPORT No. 191

Technical Evaluation Report on the Flight Mechanics Panel Symposium on Ground/Flight Test Techniques and Correlation

This document has been approved for public release and sale; its distribution is unlimited.

DTIC FILE COPY

NORTH ATLANTIC TREATY ORGANIZATION

DISTRIBUTION AND AVAILABILITY ON BACK COVER

AGARD-AR-191

NORTH ATLANTIC TREATY ORGANIZATION

ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT

(ORGANISATION DU TRAITE DE L'ATLANTIQUE NORD)

AGARD Advisory Report No.191

TECHNICAL EVALUATION REPORT

on the

FLIGHT MECHANICS PANEL SYMPOSIUM

on

GROUND/FLIGHT TEST TECHNIQUES AND CORRELATION

by

John Williams
Aeronautics and Astronautics Department
Southampton University
Southampton, Hampshire, England

This Advisory Report was prepared at the request of the Flight Mechanics Panel of AGARD

THE MISSION OF AGARD

The mission of AGARD is to bring together the leading personalities of the NATO nations in the fields of science and technology relating to aerospace for the following purposes:

– Exchanging of scientific and technical information;

– Continuously stimulating advances in the aerospace sciences relevant to strengthening the common defence posture;

– Improving the co-operation among member nations in aerospace research and development;

– Providing scientific and technical advice and assistance to the North Atlantic Military Committee in the field of aerospace research and development;

– Rendering scientific and technical assistance, as requested, to other NATO bodies and to member nations in connection with research and development problems in the aerospace field;

– Providing assistance to member nations for the purpose of increasing their scientific and technical potential;

– Recommending effective ways for the member nations to use their research and development capabilities for the common benefit of the NATO community.

The highest authority within AGARD is the National Delegates Board consisting of officially appointed senior representatives from each member nation. The mission of AGARD is carried out through the Panels which are composed of experts appointed by the National Delegates, the Consultant and Exchange Programme and the Aerospace Applications Studies Programme. The results of AGARD work are reported to the member nations and the NATO Authorities through the AGARD series of publications of which this is one.

Participation in AGARD activities is by invitation only and is normally limited to citizens of the NATO nations.

The content of this publication has been reproduced
directly from material supplied by AGARD or the author.

Published June 1983

Copyright © AGARD 1983
All Rights Reserved

ISBN 92-835-1454-8

Printed by Specialised Printing Services Limited
40 Chigwell Lane, Loughton, Essex IG10 3TZ

CONTENTS

Accession For

A

TECHNICAL EVALUATION REPORT OF THE SYMPOSIUM ON "GROUND/FLIGHT TEST TECHNIQUES AND CORRELATION"

(Cesme-Izmir, Turkey, 11-14 October, 1982)

by

John Williams

Aeronautics & Astronautics Department, Southampton University
Southampton, Hampshire, England.

1. Introduction

In predicting and guaranteeing the flight characteristics of new projects to the definition-levels /cost-restraints/time-scales demanded, while of course specifying optimum aircraft configurations, the aircraft engineer is continually faced with enormous difficulties, some of long-standing acquaintance and others quite new. Moreover, these problems are usually aggravated by a variety of complementary factors over some of which he has no direct control, relating for example to:-

- The interdependency of aircraft design features and the variation of allied prediction requirements according to the character and time-scale of the particular project.
- The variation in levels of sophistication and reliability of the required prediction methodology according to the development stage of the on-going project.
- The deficiencies of the prediction methods available in each particular discipline (e.g. aerodynamics, structures), including restraints as regards time, effort and facilities deployable at the time.

The interdependent elements of aircraft flight prediction falling within the province of the AGARD Flight Mechanics Panel relate naturally to:-

- Aircraft Performance; e.g. airfield, range/radius/loiter, climb/combat
- Aircraft Dynamics; e.g. handling qualities, manoeuvre limitations, spin and recovery.
- Store Behaviour; e.g. carriage, release, delivery.

Specialised prediction and correlation techniques may rely primarily on theoretical calculations (e.g. computational fluid dynamics), ground test facilities (e.g. windtunnels/simulators), or flight test; the relative priorities will vary in the preferred treatments for different practical problems of performance and dynamics. While some degree of constructive competitiveness between the separate prediction tools can be profitable, their complementary nature in practice will be emphasised (see Fig.1). Moreover, the profitability of their joint improvement in the future, as well as individual advances, must be frequently re-assessed, so that prediction efforts can be continually directed towards their better integration and interdependent exploitation.

Over seven years have elapsed since the first Flight Mechanics Panel Symposium focussed attention on the test techniques then available, both ground-based and in flight, for the development of new aircraft[1]. Consequently, a further FMP Symposium entitled "Ground/Flight test techniques and correlation" took place during 11-14 October, 1982, at Cesme (Izmir, Turkey), attracting about 100 participants. The four-day programme was subdivided into six sessions which covered in turn the following topics:- introductory survey papers, performance correlation, flying qualities, aeroelastic effects, subsystem correlation and round-table discussion. The significant features and major deductions of the individual presentations are briefly reviewed here as appropriate under the broadly similar but more explicit headings of the TER sections 2 to 6. Additionally, these sections include relevant comments from a prior detailed synthesis[24] of responses to an FMP questionnaire, which was prepared initially to precede and stimulate the round-table discussion.

The five specific questions were phrased as follows by the FMP Technical Program Committee (Ph. Poisson-Quinton and F.N. Stoliker):-

1) What are the advantages/disadvantages of different prediction techniques?

2) What portions of the flight regime cannot/should-not be addressed by ground-based techniques?

3) Are there areas where analytical predictions can be better than windtunnel and/or simulation results; or vice-versa?

4) Are there methods of reducing differences between prediction and flight-test results?

5) Are there any new prediction techniques that should be emphasised?

In posing the advance questions to experts selected nationally by six NATO countries (US, UK, NE, IT, GE, FR), no special guidance was given to the recipients concerning the intended scope or precise meaning of the technical terms used, which allowed wider and stronger expression of personal interests and opinions. Indeed, the informal nature and useful extent of the responses before the Symposium was very rewarding, comprising well over 10,000 words without counting some supporting published papers.

This Technical Evaluation Report has therefore used the Synthesis of Questionnaire Responses and the Round-Table Discussion, as well as the views expressed in the Technical Papers and associated debates. Status reports are made on aerodynamic performance prediction (facilities, aeroplane performance, store drag, propulsion performance, helicopter performance). Also, flying qualities prediction, structural design aspects, and two sub-systems are considered. Finally, summaries are included of the major conclusions and recommendations for action.

2. Aerodynamic Performance Prediction and Correlation

2.1 General aspects

An introductory survey by Ph.Poisson-Quinton[1] (ONERA, FR) first usefully recalls the major conclusions derived from the FMP Meeting in Valloire (1975), namely:-

- Difficulty in defining the lowest test Reynolds number which gives flow conditions adequately representing those of actual flight conditions. There is need for windtunnel testing at a Reynolds number as close as possible to the flight value.
- Many of the problems ascribed to Reynolds number effect are probably a result of inadequacies in modelling techniques; walls and support effects, flow quality, detailed model representation aeroelastic deformations, roughness for transition, etc.
- The computer will play an ever-increasing role; for interpretation/correction/extrapolation of windtunnel results, and for theoretical predictions used to reduce testing time and cost.
- There is a need for more direct communication between flight, windtunnel and design personnel.

The ground-based testing facilities developed at the various national laboratories over the past seven years include new high Reynolds number tunnels (air and cryogenic), novel computer-controlled rigs, CCV equipped models, more representative simulators for the analysis of flying qualities. Corresponding in-flight testing advances, particularly as regards analysis of the aerodynamic and structural characteristics of new configurations, include use of remotely-controlled models, experimental aircraft and flying simulators, and prototypes specially equipped as 'laboratory test aircraft'. Additionally, it is stressed that sophisticated computational methods based on the use of new electronic computers can supply powerful elements not only for more elaborate theoretical calculations (Fig.2), but also for the correlation and interaction of theoretical and experimental techniques, offering complementary assistance to the project engineer at every stage of development of a new aircraft.

2.2 Windtunnel testing techniques

The dramatic increase in the complexity and cost of most new testing facilities over the years, as for most new aircraft projects, must of course be acknowledged and justified. The paper provided by T.W. Binion[2] (AEDC, US) jointly with X. Vaucheret and X. Bouis (ONERA, FR) discusses the commendable reponse of windtunnel operators to customers natural demands for greater test effectiveness, as regards not only improvements in the data quantity and quality obtainable, but also for increases in the proportion of directly applicable information and reduction of the test cost per data unit. For example, the rate of acquisition of steady-state aerodynamic data has risen about ten-fold in some tunnels over the past decade to meet measurement requirements for military and civil projects. Better data quality is being achieved by improving tunnel flow uniformity, by reducing and correcting adequately for model support interference and tunnel wall constraints, by improving simulation and measurement techniques, and by continually appreciating and striving for significant accuracy. Correspondingly, efforts towards increase of information have stimulated improvements in model and environmental simulation and in instrumentation systems (analog and digital electronics.). Inter-related cost reductions have followed by developing methods of obtaining only the required information (e.g trimmed polars) rather than full data matrices, by taking data faster (e.g. continuously variable model condition), by testing at the lowest possible Reynolds number and by applying new computational techniques to plan, correct, verify, extrapolate and interpret test data.

Admittedly, this paper on progress in windtunnel test techniques and in the corrections and analysis of results does not provide an exhaustive review of recent innovations in windtunnel operation; thus aeroelasticity and active-control considerations are to be discussed later; while cryogenics and adaptive-wall tunnels, together with on-line wall interference assessment in conventional tunnels, are not yet considered ready for regular customer usage. However, the AEDC and ONERA experience here illustrates well the relations between customer needs and test improvements, implying that relevant ongoing improvements make up an essential fundamental aspect of tunnel work which must be strongly supported and integrated with computer programs but is seldom challenged by them!

2.3 Aerothermodynamic flight studies for space-vehicle re-entry

Systematic approaches for integrating the best of ground tests, flight simulators and progressive flight trials have to be developed to expedite safe expansion of the permitted flight envelope, as well as for profitable data correlation purposes. The paper by J.K. Hodge[3A] (AFIT/US) in conjunction with P.W. Phillips (AFFTC/US) illustrates this with special reference to determining the aerothermodynamic flight envelope allowable for a manned lifting re-entry vehicle, namely the US 'Columbia' space orbiter. The technique here consists of first integrating predictions and ground test data for the heat transfer to critical points on the Orbiter Thermal Protection System (TPS) into the flight simulator; the da[illegible]s to be scaled to flight conditions and appropriate simulator equations selected for use in a real-time man[illegible] loop facility. Next the simulator can be used for first flight planning, parametric studies and design [illegible]ient flight manoeuvres in order to enhance both flight test data reduction and flight envelope expansion. Then, after the flight test, best estimates of simulator parameters are derived by a data reduction technique (for the imbedded thermocouples) which is based on systems identification theory. Thence the original simulator parameters are updated, with perhaps a conservative bias, and the procedure is repeated through future flights; envelope expansion is thus accomplished throughout with safe transient test manoeuvres. Such modern flight data reduction techniques could also be valuable in analysing windtunnel data to reduce test time.

More generally, flight-derived aeronautical data can likewise be employed to update the predicted data base, expand the flight envelope, update crew training and engineering simulators, improve the flight control system design and qualify predicted placards; all in addition to verifying ground-test facilities, aircraft modelling and analytical prediction techniques.

2.4 Hypersonic/high-incidence conditions for space-shuttle re-entry.

The space-shuttle orbiter re-entry programme offered an excellent opportunity to attempt meaningful correlations between windtunnel and flight test data for manned manoeuvring of an unusual aerodynamic vehicle over a very wide range of speeds, from hypersonic gliding re-entry to subsonic horizontal landing. The paper by P.W. Kirsten[3B] (AFFTC,US) compares flight-determined performance (lift and drag) and stability and control derivatives to pre-flight predicted data, for the initial three re-entries of the space shuttle orbiter, from Mach 25 at 100 km height to Mach 0.4 at 1 km height. Because a conventional progressive flight test build-up before the shuttle's first mission was precluded, over 27,000 hours of windtunnel occupancy were spent obtaining aerodynamic data from virtually every major facility in the USA. Moreover a special simulator was dedicated to the development and design of the three definitive types of test manoeuvres to be performed during each flight re-entry. Extraction of the flight test data was achieved by an elaborate onboard instrumentation system, including computation of the parameters required to define the instantaneous flight condition and vehicle Euler angles.

At the angles-of-attack so far tested in the orbiter programme, the lift-to-drag ratio for supersonic/hypersonic flight conditions is well predicted. The subsonic lift-to-drag ratio is some 10% greater than predicted, associated with a misprediction of drag coefficient. More generally, although good correlation is achieved between flight and prediction, some differences occur at high Mach numbers and attitudes. In particular, the basic longitudinal pitching moment (C_{mo}) of the orbiter is significantly different from that predicted above Mach 8, probably because of real gas effects at high altitudes. Likewise, the interaction of the yaw reaction control jets with the aerodynamic flow field is over-predicted at low dynamic pressures, due to incorrect extrapolation from available windtunnel test conditons to very low dynamic pressure flight conditions early in the re-entry. Any such adverse correlations should not be used unjustly to criticise ground-based facilities alone but rather as constructive pointers towards improving the overall data prediction and acquisition process. For example, questions can be raised here as to the real accuracy of the angle-of-attack and sideslip-angle data from the flight tests, particularly since the former was derived indirectly from drag measurements.

2.5 Transonic wing design on subsonic/transonic fighter aircraft.

The main points of performance prediction and correlation interest here relate to three-dimensional effects on moderate aspect-ratio wings, characteristics of a transonic wing design throughout a broad C_L-M region, effectiveness of manoeuvre flaps on a transonic wing, and behaviour at and beyond the buffet boundary. The paper by D. Jacob[4A] (Dornier/GE) compares windtunnel and flight results for lift drag and buffet from an experimental programme with a special transonic wing design (TST) on the Alphajet as a test vehicle. Extensive tunnel tests were performed with a low-speed complete model of 1/5 scale and with a high speed complete model of 1/10 scale. The aircraft flight test programme comprised about 110 flights, the right-hand half-wing being fitted not only with strain-gauges and accelerometers, but also with static pressure tubes and dynamic pressure probes over 4 streamwise sections. Complementary ONERA tunnel tests of this actual half-wing (plus dummy half-fuselage) provided valuable duplication of flight testing conditions, including representative aeroelastic behaviour at full-scale and actual flight instrumentation.

The tunnel model and flight test results for the aircraft lift vs drag polars (C_L vs C_D) agree quite well; the drag rise Mach number is well predicted by the tunnel; the C_{Dmin} values measured with transition fixed on the model are in better agreement with flight than those with model transition free; but the lift-incidence curve slopes (trimmed) are noticeably lower in the tunnel than in flight. The maximum trimmed lift coefficient for the clean aircraft configuration is again some 8% lower in the tunnel than in flight, and as much as 20% lower for the landing configuration. While this deficiency is partly due to Reynolds number effects (1×10^6 c.f. 9×10^6), it is also commensurate with trends from the tunnel steady state to the flight deceleration state ($\approx$ 1 kn/sec). Reasonable tunnel predictions of flight buffet onset is demonstrated from kinks in the wing-root-bending-moment vs incidence curve (C_B vs α) and from correlation at $1/2^o$ incidence beyond kinks in the C_L vs α curve. But a reliable prediction of higher buffet levels is not yet considered possible. Discussion cautioned against the general use of measured kinks in the C_L vs α curve to predict buffet onset rather than kinks in the C_m vs α curve for normal acceleration considerations. Other comments suggested that the measured C_L value for moderate buffet tended to increase with flight altitude, implying an oscillatory -g rather than coefficient limit.

For the reliable assessment of both the good and poor aspects of such tunnel-flight correlations, some clarification of the relevant wing flow characteristics is of course needed. For the TST on this Alphajet experimental aircraft,a complementary paper by H. Buers[4B] (Dornier/GE) in conjunction with V. Schmitt (ONERA, FR) compares the surface pressure distributions from tunnel measurements on the 1/10 scale complete model and on the full-scale right-hand half-wing (plus dummy fuselage) against those from flight tests and from potential theory for transonic flow. While correlation of the tunnel and flight results is in general encouraging, there are some important differences particularly near the supercritical flow region on the wing upper surface. Moreover, the Reynolds number effects between tunnel model and full-scale could not be clearly identified, probably being of the same order as other effects associated with accuracy of measuring equipment, geometrical and aeroelastic differences between model and real wing, and other tunnel/flight data corrections. Although the authors refer to reasonably good agreement between the theoretical pressure distributions and flight, this is hardly justified except in that the wing shape is also said to be complicated. Wake measurements made on the full-scale half-wing in the tunnel are consistently thicker than those measured in the flight tests, so that the wake drag is correspondingly larger in tunnel than flight up to the divergence point. Comments implied that at the higher Mach numbers, upper and lower surface shocks had been observed on the wing; but wake-pitot traverses under these conditions in flight could not cover the practical extent of shocks.

2.6 Boundary-layer transition Reynolds numbers.

The location at which the surface boundary-layer changes from laminar to turbulent flow influences boundary-layer growth and has a significant effect on boundary-layer/shock interactions or flow separations. These can differ significantly with scaling up from model to full-scale vehicles, so that the transition Reynolds number based on the transition point and on the unit Reynolds number are considered key parameters in the overall similitude of the flow. The paper by D.F. Fisher[5] (NASA Dryden/US) and S. Dougherty (Rockwell/US) discusses the flight and windtunnel correlation of transition and fluctuating pressure data acquired during the past decade on a standard test body (AEDC transition cone). The same instrumentation and technique were used over a wide range of Mach and Reynolds numbers in 23 American and European tunnels and in flight with the cone mounted on a boom in front of an F.15 aircraft, at near zero incidence and heat-transfer.

There is good correlation between the end-of-transition Reynolds number Re_T obtained in the low-disturbance tunnels and in flight, up to about M = 1.2, while at higher M the correlation deteriorates; the flight Re_T being 25% to 30% higher than the tunnel Re_T at M = 1.6. For the higher disturbance tunnels, the Re_T values tended to be lower and there is very poor correlation between tunnel and flight. Overall, Re_T correlated also within 20% against the surface fluctuating rms pressure level. Broad peaks in the power spectra density distribution for the fluctuating surface pressure indicated to the authors that Tollmien-Schlichting waves are the probable cause of transition in flight and at least in some of the tunnels. Although significant effect of unit Reynolds number is manifest as usual in the tunnel data, little was observed in flight. A strong heat-transfer influence on transition is confirmed by the flight data, delayed or accelerated transition occurring according as the boundary-layer was cooled or heated. Further discussion noted that Tollmien-Schlichting wave mechanisms can define the onset-of-transition (Re_t), but turbulent spot growth needs to be considered for the end-of-transition (Re_T), especially important since the ratio Re_t/Re_T may lie between one-half and unity according to test conditions.

2.7 Turbo-fan engine interference on subsonic transport aircraft.

Recent transport aircraft development and flight testing has clearly shown important engine-airframe interference effects for wing-mounted engines, particularly with the trend towards twin-engined aircraft, which leads to the larger influence of one-engine failure take-off considerations on overall aircraft economy. Extra research and development thus becomes worthwhile to realise even small drag reductions and more accurate drag prediction for this engine-out condition. The paper by B. Ewald[6] (VFW,GE) stresses the particular need for reliable simulation of the engine on low-speed windtunnel models, especially for second-segment climb studies. Conventional testing methods involving free-flow nacelles, ejector-flow simulators or jet-blowing nacelles are no longer adequate. Fortunately, much better simulation simultaneously of both intake-flow and efflux momentum is now achievable retaining a realistic nacelle shape, by new air-driven turbo-fan units (TPS built by Tech Development Inc., US). Admittedly, such tests with the TPS units warrant especially careful planning and running-time minimisation, because of the increased costs, power requirements, staff demands and TPS-maintenance needs.

The recent tunnel experiments by VFW with a well-proven small TPS unit (5 inch fan diam.) on a 1/16 scale half-model of Airbus A.300 include not only force measurements, but also oil-flow visualisations on wing, pylon and engine, static pressure measurements on wing and nacelle, and wake-flow investigations behind the engine. These test techniques proved very useful to describe the influence of engine power setting on the neighbouring flow field, to predict the influence of modifications on aircraft drag, and to compare different aircraft in respect of jet-induced drag effects on the airframe. Engine-airframe interference affects considerably the nacelle itself, so the nacelle forces also need to be measured, while the external flow around the engine has an effect on the thrust so calibration under static conditions needs careful interpretation. Good agreement is claimed between the tunnel and flight results as regards the trends of interference effects, but in some cases the tunnel gave smaller interference drag values than flight. Possible causes may be postulated as low Reynolds number and absence of asymmetric full-scale effects on the half-model in the tunnel, along with possible accuracy shortfall in the flight tests. The recent developments of TPS units, to cope with the higher loadings in pressurised tunnels and with fan diameters up to three times larger should help resolve such tunnel test doubts when used on complete models as well as half models. Perhaps it should be added such TPS unit development with a fan diameter of 16 inches will soon permit a 1/6 scale simulation of a large engine appropriate to an Airbus model, but involves a shaft drive of about 1000 HP!

Further discussion noted that simulation of relative movement of the ground with a fixed model in the tunnel would be important for take-off first segment, landing touchdown and ground-roll considerations, even though of no significance for the second segment performance predictions of primary interest in this paper. Jet efflux interference on the engine pylon was also observed as significant in relation to aircraft lift and drag prediction. Additionally, the equal importance of jet mixing representation (not merely nacelle geometry) for engine-airframe interference studies in cruise was stressed.

2.8 Wide-body and rear-mounted nacelle interference on small aircraft.

Modern turbo-fan executive-type aircraft, developed for fuel-efficient comfortable transportation at high subsonic cruise speeds, now take advantage of advanced supercritical wing design techniques. But the wide-bodied fuselage and the large aft-mounted engine nacelles can lead to adverse aerodynamic interference, more dominating and different from those for underwing engines on large transport aircraft. The paper by F. Mavriplis[7] (Canadair, Canada) discusses the theoretical methods, windtunnel experiments and flight tests used to ensure an acceptable configuration and to predict performance for the Challenger executive aircraft. The wing was designed with the aid of the Jameson transonic-wing computer code (FLO22) which essentially solves the full potential transonic equation for an isolated wing of arbitrary thickness, twist and camber distributions, and dihedral. Additionally, for analysis of the wing in combination with the wide-body and fairing geometry, a perturbation treatment was devised which first used an inviscid subsonic panel method (WB Aero) to calculate the flow angles on a vertical plane through the wing body junction and then applied this to the Jameson method.

From the high-speed tunnel experience on the supercritical wing-body combination, free-transition testing is recommended at Reynolds numbers not less than about 5×10^6 for force and pressure data. The interference effects of the fuselage and fairing are not only strong at the wing root, but also extend out to the wing tip. The theoretical predictions of wing pressure distribution (with body effect) correlate well with tunnel results up to M=0.7, but deteriorate at about M=0.8 particularly inboard. Good agreement is also evident between tunnel and flight measurements of wing pressures, except at the wing-root and mid-aileron stations, where the disagreements are considered to reflect local differences between the model and full-scale configurations as tested. The tunnel model C_L- values for trailing-pressure divergence are shown to correlate well with those for the onset of buffet in flight, while the consecutive kinks in the model lift-incidence curves broadly indicate the regions of light, moderate and heavy buffet in flight, over the range M=0.3 to 0.85.

The high-lift systems for the aircraft were designed with the aid of two-dimensional multi-element aerofoil theory for optimisation of the flap and vane section geometry. From the low-speed tunnel experience, careful transition fixing close to the leading-edge of the relatively blunt aerofoil nose seems essential under high-lift conditions, and the chord Reynolds number should not be less than 2×10^6. The author then considers that the model predictions of flight stalling characteristics, including pitching and rolling moment characteristics, are quite good and that the full-scale $C_{L_{max}}$(1-g flight) is adequately estimated by incorporating DATCOM corrections for Reynolds number and Mach number.

Further discussion stressed the importance (in correlation studies) of declaring the specific model configurations and flow conditions assumed for comparison of theoretical/tunnel predictions with flight measurements on a tailored and trimmed aircraft. Although significant advances can now be made by increasing the capability of full potential flow transonic methods to compute the flow around complete configurations, it was admitted that the combined interference effects from nacelle geometry and through-flow are still difficult to treat theoretically. Moreover, mutual interference between the wing, fuselage and nacelles in combination can occur with such closely-coupled configurations. The practical need for investigation of potential-flow interference effects in cruise is now considered even more important than that of boundary-layers.

2.9 Combat aircraft afterbody development

For combat aircraft in high-speed low-altitude flight, zero-lift drag becomes dominant and care is needed to keep afterbody drag to a minimum. Windtunnel testing with afterbody model rigs is essential, measuring airframe axial force separately from powered-nozzle forces, to ensure reliable configuration development for minimum drag. Possible stability and buffeting effects from geometrical changes are, of course, equally relevant as regards handling characteristics. The paper by D.C. Leyland[8] (B.Ae, UK) discusses the tunnel model testing programme and allied flight testing concerned with Tornado afterbody development, which provided the additional rare opportunity of retrospective model research to be made after (as well as before) flight checks of particular configurations.

The experience showed that optimisation for drag can be achieved by afterbody-model tunnel testing using the B.Ae. earthed nozzle technique with independent measurements of afterbody force, nozzle thrust and combined thrust-minus-drag; model drag measurements appear to be substantiated by flight drag measurements, within the accuracy of the flight data. Tunnel and flight-measured pressures broadly agree, and significant differences are probably due to differences in base representation. A correlation of drag with base pressure obtained from model tests gives a good monitor of drag changes in flight development, but boat-tail pressures did not prove particularly useful. While major effects on drag or stability can be related to flow separation, the thick boundary-layer at the end of the afterbody can give characteristics akin to flow separation; part-cones fitted into the boat-tail gully on the Tornado installation proved to be a very good means for reducing the feed forward of base pressure oscillation and thus for reducing vibration to low levels. Usually, vibration is a good measure of flow quality, and lowest vibration gives lowest drag for a given basic geometry.

Comments stressed the problems of afterbody optimisation (boat-tail/base-area) for combat aircraft, particularly with twin-engined configurations and thrust reversers. Even small shape changes can have large effects on drag, buffeting and stability, so it is recommended all projected design modifications should be first checked as part of the model development programme, with close representation of detail on the model including possible variable geometry over the flight envelope. Afterbody interference effects are again considered to be of even more practical importance currently than boundary-layer effects, at least from performance aspects. In future tunnel tests and flight development, high-response pressure instrumentation in critical regions is recommended strongly, with matched pressure tappings on the model and aircraft. For checks on stability derivatives, tunnel tests on a complete model incorporating a representative aircraft geometry are naturally required, before testing with a distorted afterbody to allow through flow; and optimisation for stability may well also demand flight development. The possible interplay between afterbody unsteady pressure and wing buffeting behaviour should also not be ignored.

3. Status of Aerodynamic Performance Prediction

3.1 Aerodynamic prediction facilities (CFD, Tunnel, Flight)

During the past decade, the progress with CFD (computational fluid dynamics) has been substantial, largely because of the remarkable improvements in the cost-effective capabilities of computer hardware and software, facilitating the more rapid numerical solution of elaborate mathematical models, and thereby making tractable more sophisticated aerodynamic frameworks than hitherto conceivable. Expected CFD trends[1,24] embrace more complex applications of the present established panel methods for treatment of airframe surfaces, propulsors and wakes under subsonic conditions (along with boundary-layer calculations), and of small perturbation treatments under transonic conditions; developments are in hand towards full potential equation treatments for irrotational flows; next to Eulers equations (without viscosity) but for rotational as well as irrotational flows; then, hopefully within 20 years, to treatments of the full Navier-Stokes equations with adequate description of most flow regimes of practical interest. Major computational requirements for immediate progress in CFD naturally demand increases in available computer storage, further improvements in display/interpretation capabilities, and greater flexibility for program modifications on-line.

It is sometimes postulated that CFD can offer already better prediction and design capabilities than experimental investigations. However, available mathematical algorithms for computer programs are still quite inadequate to treat many practical types of boundary-layer transitions or local separations, gross separations/hysteresis, shockwave interactions, component interference, buffet, etc. For a long time to come, the engineer will have to turn to the windtunnel for adequate forewarning/prediction and reliable alleviation of some well-known aerodynamic problems and of some others not yet foreseen.

The major progress in windtunnels, as regards scale effect considerations, has resulted from the following developments stressed by Poisson-Quinton[1]:-

1) The NASA Ames 'full-scale' tunnel has been modified by repowering the existing closed-return circuit (27 MW to 100 MW) to achieve a higher top speed (100 m/s to 150 m/s) in the existing test-section (24m x 12m), together with the addition of a new open-return leg to provide an alternative larger test-section (37m x 24m, 50 m/s). Apart from the capability of subsonic testing at Reynolds numbers and Mach number (or sizes) nearer to full-scale, the incorporation of lower-noise drive fans and more acoustic treatment of test-section boundaries should provide quieter and less reverberant conditions for aeroacoustic research on rotorcraft at least.

2) The new German-Netherlands DNW subsonic tunnel located at NLR started operation in 1980, being designed to have three interchangeable closed test-sections (9.5m x 9.5m, 8m x 6m, 6m x 6m) with top speeds ranging from 60 m/s to 150 m/s. The test-section region is exceptionally quiet, because of the quiet drive-fans and acoustic treatment of the tunnel circuit, while an open test-section (8m x 6m) surrounded by a large acoustically-lined working chamber has been specially developed for aeroacoustic research on aeroplanes and rotorcraft.

3) Two new pressurised subsonic tunnels, the ONERA Fouga F1 (4.5m x 3.5m; $p_{stag} \leqslant 4$ bars, $V_{max} = 130$ m/s) and the RAE Farnborough 5m (5m x 4.2m; $p_{stag} \leqslant 3$ bars, $V_{max} = 120$ m/s), now permit the analysis separately of Reynolds number and Mach number effects, achieving values of Re_c more than 7×10^6 on complete models with high-lift systems at practical take-off and landing speeds.

4) The further exploitation of existing transonic tunnels, in particular the ONERA Modane S1 (8m diam) and the NASA Langley 8 ft (2.4m x 2.4m), has enabled profi able duplication of high-speed Mach number and Reynolds number conditions on actual aircraft components or large wing sections. Similar considerations of course remain important for supersonic tunnels.

5) Cryogenic technology developments in both America and Europe have established that tunnel test Reynolds numbers can be increased accordingly by a factor of 4 for a given stagnation temperature and pressure at a prescribed size. Following on construction of several small pilot facilities, two new cryogenic tunnels are being completed, namely the NASA Langley transonic NTF (2.5m x 2.5m; $Re_c = 120 \times 10^6$ at $M = 1$) and the DFVLR Porz-Wahn subsonic facility (2.4m x 2.4m; $Re_c = 8 \times 10^6$). The European Transonic Cryogenic ETW project (2.2m x 2m; $Re_c = 50 \times 10^6$ at $M = 0.9$) continues under study by the joint team from NLR/ONERA/RAE/DFVLR. Some reservations still remain at this early development stage about the scope of applicability of cryogenic tunnels, because of the new operational and model problems associated with their very cold testing environment (-150°C) and their more sophisticated instrumentation requirements.

As regards tunnel ancillary equipment, the electronic computer now plays an ever increasing role in the acquisition, reduction, correction, correlation of test data; so that there has already resulted a spectacular step forward during the past decade with respect to the speed/accuracy of analysis and correlation procedures. Moreover, the computer's role in tunnel experiments can now be extended, through the interactive selection of experimental model types and test conditions by computational fluid mechanics, followed by rapid feedback of experimental results into revised mathematical modelling, in a much more direct and integrated manner than hitherto and eventually on-line. Additionally the different deficiencies in mathematical and experimental models, for treating practical full-scale aerodynamic problems, serve to stress that the apparently competitive tools of CFD and windtunnel must still essentially provide mutual support.

For the evaluation of tunnel wall constraints, with both plain and ventilated test-sections, improved methods have of course been developed. Adaptive-wall techniques, with a computer-in-loop to monitor the wall deformation maintaining an unconstrained streamline environment around the model, are very promising though not yet in general use. Of course, many other conventional considerations still trouble us, often aggravated by the continuing demands for higher flight efficiency and lower prediction errors. For example, we can recall model support interference (magnetic suspension development seems limited to small models), effects of heat-transfer, waviness, joints, excrescences on boundary layers at full-scale; and adequate correlation of airframe deformations between full-scale and model-scale. Fortunately, the continuing development of air-driven engine simulators and multiple balance systems should facilitate more realistic powered-model investigations and better resolution of mutual interferences between the aircraft components.

Flight test experiments to improve prediction methods have also become vastly more sophisticated over the past decade or so, in order to provide rapidly more accurate quantitative data, rather than qualitative information only suitable for broad correlation with precise tunnel and theoretical investigations. For example, controlled dynamic manoeuvres with greatly improved instrumentation and systems can now yield much more data per flying hour and ensure better data repeatability. Moreover, with the advent of high capacity computers and more powerful software, both performance parameters and S&C derivatives can now be routinely extracted from such flight tests. This in turn allows immediate and more confident checks of flight-safety and of profitable flight test procedures using ground-based simulators, thereby supporting flight-envelope extensions into areas closer to performance and handling limits. Indeed, for such flight experimental programmes, Stoliker[24] stresses that test pilots may usefully spend several hours on an advanced simulator (updated daily) to prepare for the next one-hour flight test.

Of course, the immense increase in the onboard flight avionics capability that is combined with the computer can lead to large amounts of onboard software that must regularly be evaluated, often under adverse conditions. Consequently, flight test engineers have now to be continually prepared for more advanced avionics and computer applications in flight, while a back-up data reduction facility must be readily available, preferably at the flight test-centre itself and with some on-line output at least for continual programme control and guidance. For advanced data analysis, elaborate parameter identification procedures are now being applied, which can provide unbiased evaluation of the mathematical model parameters (or derivatives) taking account of both modelling process errors and measurement scatter by using maximum-likelihood/Kalman-filtering techniques.

Nevertheless, all this does not reduce the need for complementary applications of windtunnels and CFD with flight, to improve aerodynamic understanding and validate mathematical frameworks, even to the extent of testing special experimental and mathematical models for this purpose. Moreover, from flight we need not only better quantitative measurements of detailed aerodynamic loading and drag components, but also of airframe deformation and propulsor flow characteristics under specific flight test conditions; in order to adequately model the particular aircraft for meaningful correlation between flight and ground-based investigations.

3.2 Aeroplane performance prediction

This major topic in respect of aircraft design and cost-effectiveness attracted much critical comment, but largely of qualitative rather than quantitative nature, partly because of commercial reticence and military constraints, though expectedly also because of the great breadth of technical coverage. The following appraisal makes use particularly of the responses to the FMP Questionnaire[24] (by US, UK, NL, IT, GE, FR), too numerous to list separately here, together with the Symposium presentations and comments by R.A. Wood[9] (AFFTC, US), D. Jacob[5] (Dornier, GE), F. Mavriplis[7] (Canadair), J. Czincenheim (MDBA, FR), C. Bore (B.Ae., UK), and E. Obert (Fokker, NE). While no areas of clear disagreement were manifest, there were strong differences in relative priority and domestic emphasis, naturally according to the aircraft type and the establishment or country concerned.

The project aerodynamicist typically starts with semi-empirical analytical methods already available in-house for prediction. Next these first predictions are modified, by assistance from new directed investigations involving windtunnel model investigations on partial and complete models, by applying elementary theoretical (parametric) frameworks to the experimental results, and possibly by guidance throughout from computational fluid mechanics studies using more complex theoretical frameworks. Then early flight test results can be applied to validate and revise the prediction process. The type of progress is further complicated because the aircraft design is essentially an interactive process, with interplay between the different practical disciplines, so that some airframe details ranging from component geometry to surface condition (rivets, gaps) may vary or not be adequately specified until prototype flight testing begins. Thus the quality of any particular estimate tends to be more a function of the time and care taken to include and declare (for rational correlation) all the possible details and higher order terms, than it is of the particular equations used. No one technique can cover all aircraft types, configurations and flow regimes. Moreover, most attempts to standardise performance estimation methodologies amongst aircraft manufacturers have failed, because of the reluctance of each manufacturer to change (or even disclose) their 'best' domestic methods, and also for lack of definitive proof of what combinations of methodologies were best for any particular situation.

Aerodynamic prediction techniques are naturally the most reliable for en-route flight conditions outside the transonic region; becoming worse where piloting technique can enter as a big factor, such as in take-off and landing, manoeuvre at high incidence, or when near excess thrust limits. In all cases, difficulties arise in defining any best analytical treatment, because the aerodynamicist is initially faced with the task of summing for example the drag of individual components of the projected aircraft (wing, fuselage, tail, etc.); while each of these component drags has itself to be built up effectively from sub-components (skin friction, protuberance, lift-dependent drag, etc.), and then component-interference and propulsor-installations contributions have to be added in.

Ground-based estimates for drag polars may sometimes correlate against flight results within a few percent but, even for cruise, some estimates are as likely to be too low as too high; over the past 20 years by as much as 20% and 10% respectively! It is especially disturbing that the drag estimates for modified versions of existing aircraft have at times been no better than the earlier estimates for the original aircraft, despite the extra experience! Nevertheless, steady extension of basic understanding and more advanced prediction methods are essential even to maintain as well as improve the ability to predict drag for new projects, because new aircraft technology will need to be incorporated and greater aircraft performance will be demanded. For correlation, flight drag can probably be <u>measured</u> to about +2% while under the best conditions, but the measurement accuracy more generally may be +5% or even higher, depending on the thrust calculation scheme and on the quantity of data available. Overall, therefore, a usable consistent book-keeping procedure for drag and thrust must be employed between prediction and flight documentation, which is capable of identifying and isolating all important force elements and test conditions involved in the comparison/correlation. This is certainly an important if difficult requirement, necessitating careful planning, in advance of and during the ground-based and flight investigations, and with the former undertaken after as well as before the latter for correlation purposes.

Some particular aerodynamic-force elements recommended for further urgent attention, as regards practical prediction methods and correlation with flight, include:-

- Minimum (or zero lift) drag variation with Mach number, surface condition, joints/gaps and air-leakages over subsonic, transonic and supersonic regimes; because fairly large differences exist between present data sources.
- Induced drag variation with lift coefficient and Mach number; the windtunnel seems to be the only reliable prediction tool until now, at least for low-speed high-lift configurations.
- Lift variation at high incidences, particularly with reference to prediction of the influence of Reynolds and Mach numbers, not only for the onset of flow separation but also for stalling and buffet penetration characteristics; additionally, the practical combinations of the aerodynamic flow phenomena with airframe structural deformation and damping must be better appreciated.
- Drag creep and divergence at high speeds; present simulations of high Re conditions in tunnels by varying location of transition bands is questionnable, while tunnel-wall interference effects still remain a problem at high C_L.
- Engine inlet spillage drag variation with inlet mass flow ratio, and engine nozzle/nacelle or nozzle/airframe interference as affected by nozzle pressure ratio and variable nozzle geometry.
- Trim drag increments due to variation in vehicle centre-of-gravity position.
- Mutual interference effects between wing-fuselage-nacelle combinations, under both low-speed and high-speed conditions, with representative powered nacelles in either forward-mounted or rear-mounted arrangements.

3.3 Store drag prediction

This topic, of such great importance to combat aircraft design and operation, was examined only in the brief Symposium presentation by J.W. Britton[9B] (RAE, UK), while none of the responses to the FMP Questionnaire dealt with this challenging area. Attention is first drawn to the scatter exhibited by typical flight data, for a given aircraft store load, implying that great efforts will be needed to reduce such scatter to the desirable level of ± 1% in total aircraft drag. The prediction techniques employed are usually based on windtunnel tests with selected detailing of the stores as believed significant and feasible at the time of the tests. Naturally, their contribution to total aircraft drag depends heavily not only on the store geometry and size, but also on the mutual aerodynamic interference according to the quantity and disposition of the stores on the aircraft. Present experience indicates that it is possible to arrive at either good or bad predictions for light, medium or heavy stores loads, and that poor predictions can be inconsistently optimistic or pessimistic, whether they are based on tests at model scale or theoretical calculations.

A major contributory factor to disagreements is the degree of detailed representation of external stores provided in tunnel models or theoretical frameworks. Such aspects as excrescences/notches/nuts and bolts, all of which are in close proximity to one another, to the store aerodynamic surfaces and to the airframe itself, can have a significant influence on the precision and relevance of predicted performance for the aircraft with all or part of its stores in position. Additionally, the drag contribution from any residual pylons can be in some cases of the same magnitude as from the stores themselves, so that adequate prediction of total aircraft drag with residual pylons also cannot necessarily be guaranteed. An up-to-date re-appraisal of the technical status and of possible improvements to installed store drag prediction techniques, by appropriate experts under AGARD auspices, should be made available.

3.4 Propulsion performance prediction

This appraisal is largely based on the responses to the FMP Questionnaire[24] by J.M. Hardy (ONERA, FR), D.C. Leyland (B.Ae., UK), E.C. Rooney (NAVAIR, US) together with the Symposium presentations[8,30] relating to propulsive afterbody design and performance prediction. Current methodology for propulsion performance prediction is built up logically by complementary application of four techniques - theory, windtunnel, static-rig and flight.

Windtunnel investigations on powered models, with propulsive afterbodies or nacelles, are particularly valuable in offering early checks of integrated performance and overall flow characteristics in a controlled aerodynamic environment, permitting well-defined variations in model parameters and model geometry. Such tunnel experiments can now be made throughout the practical airspeed range on limited complete models, or on more detailed propulsive afterbody/nacelle rigs with turbo-jet, turbo-fan or propeller flows represented; these provide much more rapid measurements of force and flow characteristics than hitherto on either exploratory or optimised configurations. Separation of definitive nozzle thrust (or prop-shaft force) from afterbody and nacelle drags is important, especially for meaningful accounting of thrust-drag elements and correlation with flight results.

Theoretical computations are particularly helpful in providing a profound knowledge of the aerodynamic flow field internally and externally, and in identifying fundamental phenomena and model changes worth detailed experimental study. Typical theoretical treatments can now embrace hodograph methods for subsonic and transonic nozzle flows, the method of characteristics for supersonic nozzle flows, related jet-mixing zone and base-pressure calculations, relaxation methods for internal and external flow calculations (subsonic and supersonic), and of course boundary-layer calculations. However, when three-dimensional characteristics are especially marked because of jet entrainment or fan-intake flow effects such as from wing-engine integration, or when transonic mixed- flow conditions with flow reversal occur such as on the rear fuselage of a combat aircraft near M=1, then the current state of theoretical computations does not lead to valid external flow predictions. Tunnel testing offers a much more reliable approach to such problems.

The complementary application of tunnel model tests and theory to propulsive afterbodies can in most respects provide a satisfactory prediction of flight performance, incorporating due allowances for scale effects, hot gases and other technological factors. However, some uncertainty is still associated with the usual specification of 'mean-values' for engine-efflux pressure and temperature, as determined conventionally at a limited number of points (rake traverse) in the flow at the nozzle exit. In practice, this is insufficient to characterize the gas flow adequately, because there exists a heterogenity of pressure and temperature both radially and circumferentially, to which fluctuations are added. An expedient procedure is therefore to make reference to supplementary ground-test measurements on the engine with flight rear-body and flight instrumentation, and thereby to introduce appropriate adjustment coefficients to the model conditions relevant to flight simulation, one relating to the size-temperature parameter ($D/\sqrt{T}$) and the other to the expansion ratio. But some more elaborate introduction of heterogenity considerations into prediction methods is desirable.

As regards flight data documentation for correlation, accurate measurement of vehicle excess thrust, propulsive force and throttle-related force increments is required for definition of the aircraft aerodynamic characteristics. Fortunately, state-of-the-art improvements in accelerometer measurement capabilities have enhanced the accuracy of vehicle excess thrust measurements. Again, measurement of power output for shaft engines is now straightforward; but the propeller and rotor data required for the conversion of engine power to installed propulsive thrust can still be inadequate. For turbo-jet and turbo-fan powered aircraft, inflight thrust must currently be deduced from inflight engine measurements (such as temperature, pressure, rotational speed) and correlation of these measurements with load-cell force measurements in a ground-based Altitude Test Facility (ATF). The accuracy of this procedure may be affected by a variety of engine test-cell/flight considerations; namely, the instrumentation and data transmission uncertainties or errors, the degree of coverage of the vehicle Mach No./altitude envelope in the ATF, the accountability of any different environmental effects (between ATF and flight) on instrumentation measurements and propulsion system performance. Because of such problems, redundancy of inflight thrust measurement methods and iterative testing of engines between the ATF and flight should be required to isolate and correct likely bias errors in the inflight thrust measurement process. For the aircraft overall, a well-defined usable thrust-drag accounting procedure must be carefully employed, essentially compatible with and consistent between the prediction technique and flight documentation process, and capable of isolating all the forces which are desired for correlation purposes.

3.5 Helicopter performance prediction

Although no Symposium presentations were directed at helicopter performance prediction, responses to the FMP Questionnaire[24] by I.C. Statler (AVRADCOM, US), T. Wood and R.R. Lynn (Bell Hel/US) and Ph.Roesce (SNIAS.M, FR) clearly revealed concern and offered constructive comments. Moreover, the needs for improved prediction of both performance and handling are likely to be aggravated by modern operational demands for helicopter cruise efficiencies and speeds more competitive with streamlined propeller-aeroplane configurations.

In general, the aerodynamic prediction techniques for helicopter rotor-blade characteristics, interference effects and rotor loads are currently all empirical; or at least semi-empirical in that these techniques may depend upon aerodynamic theory until the limits of the mathematical framework are reached, beyond which the differences are made good by substantial empirical corrections. Indeed, each helicopter design organisation tends to develop its own biased techniques, with correction factors that essentially only make the analysis satisfactory for domestic configurations which do not vary far from those on which the organisation already has experimental measurements and experience. An important example of such corrections relates to the interference of the rotor wake on the fuselage, the auxiliary rotor (tail or tandem) and any tail-unit (fin or elevator). This interference can produce performance degradation, at least in cruise or climb; but even more significantly can affect handling qualities, vibration/noise and thereby performance indirectly, in ways which would be missed by most prediction techniques.

Most fundamental differences in prediction methodology relate to the preferred modelling of the rotor wake, ranging from very simple uniform flow to highly complex free-wake analysis, often with debatable confidence, because for some applications the free-wake may prove surprisingly adequate while for others even the most sophisticated free-wake treatment is still inadequate. More generally, the prediction methods for all rotary-wing aircraft rely to a large extent on windtunnel or flight test data.

Windtunnel tests, if well-designed and carefully executed, taking advantage of modern electronics, can now provide accurate results for many flight conditions. Moreover, the tunnel still constitutes today an irreplaceable test method for airframe aerodynamics, as much for the quality of the measurements achievable, as for the detailed aerodynamic knowledge which it permits. Current theoretical techniques, even the most developed applications of potential and viscous flow frameworks, are not yet capable of resolving satisfactorily the aerodynamics of typical helicopter fuselage/rotor-head combinations, even without introducing rotor-wake interactions. However, tunnels do not usually provide accurate performance data on rotor models at very low mainstream speeds because of recirculation of the rotor wake with boundary constraints; typically the mainstream speeds may not be much below 30 m/s for conventional relative sizes of closed test-sections and models, though the lower limit may be 10 m/s with very large tunnels (e.g. NASA Ames 80ft x 120ft) or with large open test-sections. Additionally, very low speeds might be acceptable if recirculation were precluded by careful capture of the rotor wake and by its remote diffusion out of the tunnel test-section, as successfully achieved already with whirl-tower static-rig facilities (eg AVRADCOM Ames/US).

In flight testing, it has not been possible to extract adequate rotor performance data until recently, because instrumentation has been unable to separate completely the forces on the rotor from those on the fuselage. This problem is now being addressed by multi-balance systems connecting the various components, as with the new Rotor Systems Research Aircraft at NASA Ames.

Overall, the current generation of helicopter airload prediction programs is especially limited in the ability to extrapolate a given program with confidence to new or unrelated designs. Furthermore, while significant advances have certainly been made in recent years towards understanding and predicting individual aerodynamic characteristics such as rotor-blade and interference phenomena, much of this new information has yet to be incorporated into the already large computer program prediction codes for rotor airloads prediction under practical conditions. Nor have many of the sophisticated frameworks yet been checked thoroughly against complete advanced sets of experimental data.

One important viewpoint from Industry is that there has been a tendency to paint an aura of detailed prediction capability (not merely performance) in developing new aircraft and weapon systems, which has exposed the Industry to unmerciful castigation about prediction shortfalls when carrying out 'normal' development activities to overcome such problems. This implies that we must really declare possible errors in specific predictions and the likely R&D required to achieve improved standards. In respect of helicopter performance, it has been suggested that some current correlation standards between test results and prediction are as follows:-

- Hovering out of ground effect : ± 3% gross weight based on engine limit.
- OEI service ceiling conditions: ± 6% (HP) minimum power requirement and ± 25% (ft) service ceiling.
- Maximum forward speed V_{max}: ±6%
- Oscillatory blade loads at V_{max}: Prediction area is about 30% at design stage, with blade inplane loads usually underpredicted, reducing to 10% if changes from base-line blade.
- External-noise levels: ± 3dB for level flyover, ± 5dB for take-off or landing.

Another suggestion is that an increased effort should be made to develop the tools of statistical treatment for measurements effected in helicopter flight, through establishing data banks and their systematic derivation/exploitation through modern parameter identification techniques. Additionally, it is undeniable that continuing fundamental theoretical and experimental work is equally essential to improve the reliability and scope of allied analytical frameworks.

4. Flying Qualities Considerations

4.1 Combat aircraft dynamics at high incidences

Techniques to predict the flight dynamics characteristics of new combat aircraft are becoming increasingly more important as the levels of operational capability and advanced technology in the design of such aircraft continue to rise. Two design trends of particular relevance are:-

1) The growing operational requirements for a 'carefree manoeuvre' capability close to and perhaps even beyond the conventional aerodynamic limits, using a control system with built-in departure-prevention features.

2) The use of high-performance configurations which are naturally unstable and which therefore rely critically

on stability augmentation from a sophisticated flight-control system.
While mathematical modelling techniques to make predictions of aircraft dynamic behaviour and also appropriate control systems have been developed over the years, the acquisition of the necessary aerodynamic derivatives and the accurate determination of the non-linear aerodynamic characteristics at high angles-of-attack can present a stumbling block in project work. As well as extensive steady-state windtunnel tests, it is necessary to make time-dependent measurements using rotary and oscillatory model techniques in tunnels or flight, particularly in view of the inadequacy of theoretical aerodynamics (CFD) for the treatment of high-incidence conditions with practical aircraft configurations.

The new windtunnels available with higher standards of Reynolds numbers should now be used for stability and control measurements, particularly to help predict the non-linearities and boundaries at high incidences; the use of dynamic rigs for derivative measurements should be extended into these tunnels. Also free-flight models which employ active control systems should be used whenever possible to take the process further. More generally, flight motions can be governed by aerodynamic inputs which are highly non-linear not only with incidence but also with rotational rates and with dynamic head (at transonic speeds), or may have strong dynamic cross-coupling between longitudinal and lateral-directional modes of motion, or may embrace strong aero-elastic couplings. Then complementary flight research at full-scale becomes especially important, incorporating extensive instrumentation and matched parameter identification techniques for the extraction and analysis of data.

For a modern combat aircraft the development of a flight control system (fly-by-wire), capable of achieving efficient protection against loss of control of the aircraft in all its operational configurations, thus requires extremely reliable predictions of the aircraft aerodynamic characteristics. The paper by P. Mathe[10] (AMD-BA, FR) discusses the work associated with the predictions and development for the Mirage 2000 at high incidences. In addition to the conventional windtunnel model tests under steady-state conditions, a large number of other test techniques were implemented, namely:-

- Tunnel tests with forced oscillations to determine the aerodynamic derivatives (direct and cross) up to the highest incidences without non-linearities.
- Vertical tunnel tests with a rotating rig, through a large range of incidences, sideslip and rotational speeds, to determine the aerodynamic characteristics under strongly dynamic conditions up to very high incidences.
- Catapulted free-flight tests on a piloted model.
- Spinning flight free-model tests in the vertical tunnel.

The aerodynamic characteristics so determined then permitted simulator predictions of the behaviour of both the aircraft and its flight control system for each limited aircraft trial, followed by correlation checks/updating/extension of the simulator predictions before each step-by-step expansion to more extreme flight conditions.

Overall, the quality of the predictions before flight proved excellent and were an important factor in the good developments of the control system of the Mirage 2000; resulting partly from the thousands of tunnel testing hours, partly from the experience of the analysts accrued over the past two decades, and partly from the integrated conception/design/production of the electric control system within the Firm itself. Thereby any technical surprises were few and acceptable. For example, some noticeable differences between flight and prediction in respect of the yaw induced by differential deflection of the elevons in supersonic flight at low altitude was associated with aero-elastic distortion effects. Minor differences in longitudinal stability at low speeds and very high incidences were resolved by a small increase in the pitch-deflection of the elevons. Admittedly, the pitching moment changes with Mach number through the transonic regime at high incidence were much more severe in flight than predicted by the windtunnel.

The free-flight drop-model technique discussed by G.F. Moss[11] (RAE, UK) is aimed at the investigation of low-speed high-incidence flight conditions. It has been developed at RAE in conjunction with windtunnel model testing (steady and unsteady) and mathematical modelling of aircraft dynamic behaviour, first to provide further data for the mathematical models themselves and then to check out predictions of the dynamic behaviour. Briefly, the free-flight models are generally pre-programmed to execute a prescribed sequence of control-surface positions after launch, though some provision is now being made for an up-link from the ground to augment this simple system in some respects. Recently, the concept of a fully-active on-board in-loop flight-control system has been included, which is particularly useful for the purposes of high-incidence research into the design of flight-control systems and/or departure-prevention. For each free-drop, the model (typically one-quarter full-scale) is lifted from a ground trolley and towed to altitude on a long cable, where the model is launched in a flying attitude at a prescribed low forward speed - below 150 kn IAS model-scale (300 kn full- scale). The free-flight of the model can last up to 100 sec or more (equivalent 200 secs full-scale), while the model transmits data to the ground station by telemetry and is tracked by accurate radar scanners or kine-theodolite cameras. Telemetered data generally includes signals from linear and angular accelerometers, rate and attitude gyros, control-surface positions, pitot-static pressures, incidence and side-slip angles, etc. Model recovery techniques are such that catastrophies are rare and the model is normally re-usable after minor repairs and recalibration.

Over the last few years, the Tornado aircraft configuration has been investigated for research purposes in respect of the development of the RAE model technique and the derivation of mathematical models for the prediction of flight-dynamic behaviour, with free-flight trials at RAE Larkhill (UK), Woomera (South Australia) and NASA Dryden (US). Thereby[11], the free-flight technique described has been shown to be advantageous for the prediction of the effectiveness of departure-prevention-systems of new combat aircraft. Also the models data has been found to be very useful in the construction of mathematical models for the development of reliable prediction methods for the dynamic behaviour of aircraft with such departure-prevention systems. Discussions about the completed RAE free-flight work implied that the costs are substantially less than for HIMAT (US), but of course the programme content and complexity is correspondingly smaller. For simplicity, nacelles on the free-flight models have been employed without throughflow - simulating large spillage at low power conditions, possible aerodynamic inaccuracies in direct-derivatives have been neglected, and cross-derivatives have been ignored.

The forthcoming RAE programme is based on a new high-incidence research model (HIRM) of a feasible combat aircraft configuration, with a closely-coupled foreplane as well as an aft tail (both of which can be used as controls), the central objective being the widening of understanding of the flight dynamics phenomena of combat aircraft at high angles-of-attack. Much attention is being devoted to the establishment of a more elaborate consistent data bank, particularly through extensive windtunnel tests under steady-state, rotary and oscillating conditions, and to the derivation of suitable mathematical models. The free-flight drop-model trials should start in 1983 with the simplest of control systems carried on board, but other active flight control systems of different degrees of sophistication are being designed in the light of experience from the windtunnel work and mathematical model development.

Spinning is envisaged classically as a stalled aircraft phenomenon with a helical movement of the aircraft while descending almost vertically, so that the phenomenon can be reproduced on a model in a vertical windtunnel where the descent is readily simulated and where rotational motion is represented. However, modern combat aircraft can spin in a trajectory which is initially horizontal or even ascending, and which does not become vertical until after several turns, so that direct simulation by tunnel models becomes much more problematical. The paper by D. Tristrant[17B] (IMFL, FR) presents three aspects of recent analytical and experimental studies at the 'Institut de Mechanique des Fluides (Lille)' on this subject. To describe the principal three-dimensional characteristics of the spin motions for correlation between flight and model experiments, including also the extremes of deep-stall and barrel-roll, three distinctive features are first categorised; these range from flat to pitching as implied by incidence variation, from slow to rapid, and from calm to agitated.

Secondly, as regards achievements in model-to-aircraft correlations on spinning, poor agreement is said to have occurred only rarely over the 30 years of vertical tunnel testing at IFML, though when such disagreements have arisen the tunnel results have usually been optimistic (in a safety sense). Recent differences in results for a motorised glider, with correct simulation of Froude number, appear primarily to be due to low Reynolds number effects associated with particular wing geometry (outboard); this has been clarified by lift-force balance measurements on the model with wing leading-edge modifications and by corresponding free-spin tests. Thirdly, with particular reference to the modelling and simulation of the rapid flat spin of combat aircraft, it is shown how dynamic balance measurements on rotating and oscillating models in combination with steady-state measurements usefully provide aerodynamic derivatives for use with the dynamic-motion equations, thereby leading to spin simulation results suitable for comparison with model tests in vertical tunnels. Only the controls-neutral case is illustrated, in the absence of aerodynamic control derivatives. But it is evident that a good definition of the lift-drag polar is essential for the mathematical model to take into account correctly the effect of practical variations in incidence due to the rotation, and to determine the stable equilibrium condition of rapid flat spin.

An interesting observation on the importance of design for spin prevention, rather than spin recovery, was raised by C. Bore[24] (B.Ae., UK). On the Harrier wing, much care was taken to ensure that the spread of boundary-layer separation across the wings was not only slow but also the same on both half-wings. This was to avoid the phenomenon of wing rock from an unsteady aerodynamic forcing motion, and was achieved by a carefully evaluated set of leading-edge wing fences, sawteeth and vortex generators. In fact, the flow does remain symmetrical up to high incidence; so that, even if the Harrier is spun deliberately by pitching up rapidly to 30° or more and by putting on full pro-spin controls, it then spins gently and comes out immediately on centring the controls.

4.2 Aircraft buffeting studies

Because of the demand for improved manoeuvrability in the subsonic and transonic flight regimes, it has become increasingly important to predict the buffeting characteristics of an aircraft at an early stage in the project development programme, as these characteristics or their improvement may affect the choice of aircraft configurations. The simplest method of predicting buffeting from windtunnel tests is perhaps the study of slope changes in the curves of normal force, pitching moment or axial force plotted against incidence. But more sophisticated methods must be used if buffet levels are required rather than qualitative estimates of the flight conditions for onset/moderate/heavy buffet. One recent technique relies on the measurement of fluctuating pressures on a nominally rigid model, in order to help calculate the response of the real flexible aircraft structure; but expensive instrumentation and complicated data handling/analysis is required to determine the buffet excitation, while the aerodynamic damping is not measured directly but estimated. Two other 'dynamic-response' techniques now seem to be preferred, employing either conventional 'semi-rigid' models of solid steel and light alloy as normally made for steady-state force tests, or aero-elastically representative models which tend to be more expensive and fragile though may be essential also for flutter testing.

The paper by S.H. Teige[12] (SAAB, Sweden) and S.J. Boersen (NLR, NE) compares windtunnel buffeting measurements, by the 'semi-rigid' model technique, with flight measurements on the SAAB 105 aircraft (jet trainer), applying Jones method of analysis. This method is based on the assumption that a conventional windtunnel model has modes of vibration which are similar to those of the aircraft for the lower and more important modes in buffet conditions, that these can be treated as single degree-of-freedom systems with negligible aerodynamic coupling, and that measurements of unsteady accelerations are made at least at one point on an aerodynamic surface. The measured total damping is then the sum of structural and aerodynamic damping of each mode with mainstream airflow so that, if the structural damping is evaluated from a ground resonance test (no airflow) and is small, the aerodynamic damping can be simply derived. The effective aerodynamic damping of the aircraft is then obtained by direct scaling from the model test; so that, when combined with structural damping obtainable from the full-scale ground-resonance test, the aircraft buffeting response can be calculated for comparison with full scale. The windtunnel tests were made at NLR on a half-model at 1/4.5 scale mounted on a heavy strain-gauge balance, with two accelerometers mounted in the wing tip and one in the fuselage at similar positions to those on the aircraft.

The buffet response predictions for the wing-tip location are only partly successful[12]. At M=0.5, the Mach number of primary interest in this case and where the flight R_e was duplicated in the tunnel, the prediction method works well in respect of both buffet-onset C_L and g_{rms} trends beyond buffet in-flight. At M=0.7 the buffet onset is again well-predicted but not at M=0.78, probably because of the influence of the relatively large model blockage (2.5%) on wall interference with shock-waves on the model. During discussion, the opinion was expressed that blockage of not more than 0.7% would now be recommended for such half-model tests. Moreover, reliable separation of aerodynamic from structural damping is no easy task; in particular, special checks should be made to ensure that the structural damping does not vary unexpectedly with model loads, for example by testing over a range of tunnel pressures with attached flow conditions - to minimise aerodynamic damping changes.

In contrast, the paper by D.G. Mabey[13](RAE, UK) describes some buffeting measurements on a flutter model of the wing of a typical strike aircraft and compares the results with some buffet boundaries and aerodynamic roll-dampings from flight experiments. The complete-model wing was structurally based on an idealised interpretation of the full-scale aircraft, though the straight cylindrical body was unrepresentative of the aircraft fuselage and included no engine nacelles, cockpit canopy or tailplane. The wing response was monitored by 3 strain-gauge bridges on each half-wing, as provided for the original flutter tests; while other strain-gauges measured the steady bending moments, the unsteady bending moments and the unsteady torsion-moments on both half-wings. The model was tested in the RAE Bedford 3 ft tunnel over a Mach number range of 0.45 to 0.94 and a total pressure range of 0.34 to 0.94 bar. Overall, these tests confirm the natural premise that aero-elastic models can provide much more detailed and valuable information about buffeting on aircraft than can ordinary tunnel models; nevertheless, there are qualifications with respect to the related cost, time-scale and research purpose for particular models. The present tests show additionally that, with the provision of a freedom in roll for the wing, an aeroelastic model can give a sharp indication of the 'low-frequency' wing-rock boundary as well as the wing buffeting.

More specifically, these buffeting measurements on the flutter model of a wing of a typical strike aircraft suggest five main conclusions[13]:- New buffet severity criteria can be formulated for the first symmetric mode in wing bending. Buffeting coefficients previously determined from tunnel test correlations may relate to aircraft handling boundaries rather than to quantitative buffeting assessment by the pilot. On this aircraft, the handling boundary at high incidence is closely related with 'wing-rocking' caused by a sudden loss in damping due to roll of the wing. Significant variations on aerodynamic damping occur after the onset of wing flow separations, which are themselves frequency dependent except at low frequencies of the order of the rigid-body roll mode. Finally, although half-models can predict the symmetric buffeting response, complete models are needed to predict both anti-symmetric and symmetric.

4.3 Non-linear modelling from dynamic flight tests

Dynamic flight test techniques may be employed for the determination of a variety of aircraft performance characteristics (lift and drag coefficients) and of stability- and-control characteristics (e.g. moment derivatives). The creation of a data base from dynamic flight measurements can thereby permit the synthesis of non-linear aerodynamic models, plus applications of the derived model for predicting aerodynamic forces and moments in flight conditions different from those traversed in the datum flight manoeuvre, and the correlation of the results of the dynamic flight test data analysis with other data sources such as windtunnel experiments. The paper by J.A. Mulder[14](Delft Univ., NE) discusses such techniques with particular reference to non-linear model identification and development, from flight experiments by Delft University and DFVLR Braunschweig on a DHC-2 'Beaver' single-propeller light aircraft equipped with a high accuracy instrumentation system.

The data analysis process for these dynamic flight tests constitutes in principle a dynamical system identification problem. Of course, some of the system parameters such as aircraft mass and moments of inertia are known (or directly estimated), while the aerodynamic system parameters of interest can become classical stability and control derivatives when linear models are used. It is argued here that the process can best be analysed in two steps. First, the detailed flight path is reconstructed from the extensive accurate instrumentation data, resulting in a set of important time histories of actual aircraft behaviour; a data base is formed for the second step in which the aerodynamic models are identified and the time histories of the aerodynamic forces and moments are calculated. In aerodynamic model identification, selections are made from a set of candidate variables for the development of models which on the one hand result in an adequate fit to the flight measurements, yet on the other hand result in statistically significant parameter estimates and good model predictions. Statistically, significant models may well be too refined for good model predictions and, when a second set of measurements is available, the prediction capability is a better criterion in this respect. The analysis[14] has only been completed for incidences up to 12°, so possible hysteresis effects associated with separated flow conditions and stall still need examination.

Steady-state low-speed windtunnel experiments on a propeller-powered model of 1/11 scale in the Delft 1.8m x 1.2m tunnel were also made using a six-component balance rig, under both symmetrical (zero sideslip) and yawed conditions. Comparison of the dynamic flight test measurements with the results of the tunnel experiments is not considered to be possible directly, but to be dependent on the prior identification of mathematical models for the aerodynamic force and moment coefficients. Allowing for the rather low Reynolds numbers of the tunnel experiments, a reasonable correspondence exists between the tunnel results and the derived model predictions from the dynamic flight tests. Moreover, the results of such tunnel experiments can be helpful of course in synthesising aerodynamic modelling for a wider range of flight conditions, as required for example in the provision of mathematical models required for flight simulators.

The implementation of active control-system technology (ACT), for the extended use of automatic control to improve aircraft flight characteristics, demands more detailed understanding and more advanced modelling of the influence of anticipated external disturbances, aerodynamic characteristics and control system responses. Of particular difficulty is the identification of the effects and the estimation of dynamic stability parameters related to high frequency motions associated with flight in turbulence. The paper by K. Wilhelm[17A] (DFVLR, GE) and R. Verbrugge (IFML, FR) reviews their on-going research programme, correlating and comparing results obtained by several complementary techniques, particularly for the unsteady aerodynamic transient effects relevant to a gust-alleviation system, i.e. modelling of the dynamic response due to quick-acting flaps and high-frequency gusts. The techniques applied in this programme comprise theoretical prediction, steady-state windtunnel measurements, forced-oscillation windtunnel derivative-balance measurements, semi-free flying models with dynamic simulation and gust generation in windtunnel, catapulted free-flight unpowered model tests, full-scale flight tests; with application of system identification methods to get detailed information from the last three dynamic investigations. The research programme is centred on the Dornier 28 TNT configuration, a light experimental aircraft (modified Skyservant) with a new high wing (TNT) carrying twin propeller nacelles, and incorporating an open-loop gust alleviation system with servo-actuators on the quick-acting wing flaps and elevators.

From the analysis of the published experimental data, the following conclusions are drawn[17A]:-

- Even when the comparison of the results from the ground-based facilities is satisfactory, the correlation of these results to the full-scale aircraft tests remains a problem. It is therefore necessary to identify which additional effects are present in the behaviour of the full-scale aircraft and to integrate these effects in the mathematical model, apart from appreciating the increase in test Reynolds number by a factor of about ten between experimental models and full-scale.
- For the investigation of aerodynamic transient effects, dynamic measurements under reproducable well-controlled conditions (windtunnel or laboratory) are essential, and the determination of these effects is possible only if system identification techniques are applied to the measurements. The choice of suitable input signals is important for the performance of a successful system identification.
- An ACT system, such as an open-loop gust alleviation system, is very sensitive to incorrect modelling of the aircraft behaviour, and an optimised realisation of such a system is only possible if the dynamic effects can be modelled properly. In the case of sudden flow changes due to short-length gusts or high-frequency flap inputs, the description of the aircraft behaviour by using only global derivatives is not sufficient, so that it is necessary to separate the effect into several components which produce a delayed influence on the major aerodynamic surfaces.
- Future research activities with regard to modelling aerodynamic transient effects will be directed towards more exact determination of gust inputs from flight test measurements and towards further investigation of the two different approaches by DFVLR (Braunschweig) and IMFL (Lille) to modelling aircraft gust response.

As regards parameter identification techniques in general, some comments by R.C. A'Harrah[24] (NATC, US) are especially useful in categorising the major items concerned with computational methods and generalised systems approach as follows. Computational methods can be subdivided into three types: equation-error methods assume perfect measurements and optimise 'cost' functions that are based on an assumed form of modelling error (process) noise; output-error techniques assume that the model of the system is correct and optimise cost functions that are based on measurement system error models; and advanced methods account for both process and measurement noise. Examples of equation-error, output-error and advanced methods are least-squares, Newton-Raphson, and maximum-likelihood/Kalman-filtering techniques respectively. If either process or measurement noise is present, then one of the first two methods can be in error. However, when advanced methods are used, these error sources are taken into account and unbiased estimates can theoretically be obtained.

Any of these three computational techniques can be adapted into a generalised systematic approach to parameter identification, for example, that used at the NAVAIR Test Centre (Patuxent, US) which uses a five-step process. First, careful structuring and test of the input design is vital, to ensure that the flight test measurement set generated has the information content required to estimate or predict critical parameters. Secondly, flight test data processing and analysis must be performed, say by using a maximum-likelihood parameter identification algorithm, thereby estimating scale-factor errors and biases and obtaining a kinematically consistent set of measurements prior to estimation of model parameter. Model structure determination is the next step in this process, primarily to identify significant terms of a mathematical model, say by optional subset regression if systematic definition of a non-linear aerodynamic model is involved. If model structure phase is ignored in the identification process, then the model will be over or under parameterised and errors will be introduced into the final model parameter estimates. Next parameter identification follows as the last data processing step and provides the refined estimates of the model parameters, using say the maximum-likelihood technique to preclude biased estimates if both process and measurement noise are present. The final step is the verification of the model and parameter estimates, involving the use of estimation uncertainty bounds and the prediction of aircraft responses, with enginering judgement also playing a role in the verification process. This five-step approach to integrated system identification has been successfully demonstrated by NATC for predicting the non-linear model parameters of the VAK-191B VSTOL aircraft during transition and hover flight, and of the F-4S fighter aircraft in the high angle-of-attack regime where stall and departure manoeuvres were particularly analysed.

4.4 Helicopter simulator validation and test data evaluation

Rotorcraft pose a particularly difficult problem for simulation technology in that the mathematical model required tends to be even more complex than for fixed-wing aircraft, so that very large computer capacity is needed to produce real-time solutions for man-in-loop simulation, while helicopter mathematical models are very difficult to verify. Moreover, the flight characteristics of helicopters tend to have low levels of stability (or to be unstable) and there are large inter-axis couplings; characteristics which make derivation of visual and motion cues most critical. In validation of simulation fidelity, the distinction should be made between real engineering cues as sensed and recorded by instrumentation and subjective cues such as provided by visual or motion perception. A rationale may be also postulated that, if the simulator cannot provide correct pilot response behaviour (i.e. control strategy and technique), then the fidelity is inadequate.

The paper by D.L. Key[15] (AVRADCOM, USA) describes a joint Army/NASA effort to perform a systematic ground-based piloted simulator validation exercise based on the Sikorsky UH-60A Black Hawk helicopter, for which many new technology roles and military missions will evolve requiring investigation of flying qualities by simulators. This helicopter has features such as elastomeric main-rotor bearings, canted tail-rotor and variable-incidence stabilator, all of which provide a challenge in testing, modelling and verification. The first step in the simulation procedure was to obtain the best available Black Hawk mathematical model that could be run in real time on the available computer (CDC 7600). This complex model is a total force, non-linear, large angle representation in six rigid-body degrees of freedom; in addition, rotor rigid-blade flapping, lagging and pitch/torsional degrees of freedom are represented. For example, the total rotor forces and moments are developed from a combination of the aerodynamic, mass and inertia loads acting on each simulated blade, with the aerodynamics of each blade element treated as a function of local aerodynamic incidence and Mach number. The flight control representation in this model covers both the primary mechanical and the automatic systems.

To provide a basis for verifying and improving the mathematical model first by engineering experience and then analytically, flight test data has been obtained, the requirements for instrumentation and calibration being extremely stringent to meet system identification demands. The flight tests included extensive trim and static stability points and special system identification manoeuvres; as well as steps, doublets, pulses, roll reversals, pull-ups and pushovers. Data on pilot performance and control activity were also recorded while performing specially-defined mission-type tasks, so these will be used in the simulation validation part of the exercise.

Currently, work is proceeding in-house to further develop and apply statistical and parameter identification techniques in order to improve the structure of the model and refine the parameters. The flight data is being used by Sikorsky to identify deficiencies and make improvements in their basic mathematical model, and by Systems Tech. Inc. to develop analytical models for control strategy and to accommodate the effects of simulator components. The future plans are to incorporate the updated mathematical model into a NASA real-time simulator facility during 1983, at which time data will be obtained to perform the final step in the validation assessment analysis.

The complementary paper by J. Kaletka[16] (DFVLR, GE) discusses two different experimental approaches to develop and verify mathematical descriptions of rotorcraft characteristics, namely by windtunnel experiments with a model rotor and again by the evaluation of flight test data using system identification techniques. The main difficulties for helicopter windtunnel tests are proper scaling and fabrication of the rotor to achieve the transferability to full-scale helicopters. Fuselage models are usually scaled to have comparable aerodynamic characteristics. However, the scaling of the rotating rotor must provide both aerodynamic and dynamic similarity, which has three important practical implications. Firstly complete similarity between model and full-scale rotor is not possible to achieve, secondly the rotor blades must be manufactured with extremely high accuracy, and thirdly the model rotor should be as big as possible so large tunnels are need in consequence.

Rotorcraft system identification is considered a relatively complicated task because of three main problem areas. A large number of coupled degrees of freedom necessitates a high order mathematical model to adequately describe helicopter dynamics; but successful application of system identification is limited by the size of the mathematical model, the number of unknowns to be identified, and the information content of the data. Inherent rotorcraft instabilities limit the time length for a data run because increasing amplitudes quickly invalidate small perturbation assumptions used for linear models; additionally, they complicate the stabilisation of the rotorcraft at defined steady-state trim conditions and lead to large deviations therefrom when gust disturbances are present. Finally, data measurement quality is affected by the high vibration level of helicopters, while some variables are difficult to measure.

These two experimental approaches were applied to examine the B.105 hingeless-rotor helicopter characteristics[16]. A rotor test stand with a Mach-scaled B.105 model rotor (4m diam) was employed for effectively steady-state force and moment measurements in two different large tunnels, the Daimler-Benz 7.4m x 4.9m tunnel with a closed-floor-only test-section and the DNW 8m x 6m tunnel with a closed test-section. The main flight regime, except for some low-speed and steep-descent conditions, was covered with stepwise variations of rotor collective, rotor longitudinal cyclic, rotor angle-of-attack, and advance ratios. Rotor derivatives were extracted from the tunnel test programmes by calculating the gradient of the force or moment change due to a change in the control. For the parameter identification from the helicopter flight test data, dynamic tests are involved as derivatives have to be extracted from the measurements of the helicopter motion, by analysis in terms of the appropriate mathematical model. Particular attention has been concentrated on the design/implementation of the signal input and on the verification of parameter identification results.

Comparisons of static stability-and-control derivatives, as obtained from windtunnel measurements, flight parameter identification and supplementary theoretical predictions, imply that satisfactory agreement could be obtained for most of the derivatives (particularly force derivatives) when deviations attributable to basic differences in the methods are taken into account. Higher deviations of some parameter identification values for moment derivatives, from the corresponding windtunnel and theoretical predictions, indicate that planned future rotorcraft modelling for the identification process must also include the rotor dynamics - as also recommended by Key[15].

5. Aeroelastic Effects

5.1 Aeromechanical stability of tilt-rotor aircraft

Some 20 years ago, the XV-3 tilt-rotor aircraft identified a problem of possible rotor-pylon-wing instability during manoeuvres in the aeroplane flight mode, and a sustained rotor-pylon oscillation was actually encountered during NASA 40 ft x 80 ft windtunnel tests of the aircraft. Extensive analyses and model tests showed that the sustained oscillation (decreased damping) was generated by destabilising rotor forces that, at high inflow angles, could become significant in determining the coupled rotor-pylon stability. The destabilising moment is generated by the H forces that add to produce a hub shear force in the direction of the pylon pitching rate, this moment being directly proportional to blade inertia, number of blades, mast length and airspeed, but inversely proportional to rotor radius squared. The technology base thus derived made possible the analytical prediction of the structural aeroelastic stability of the XV-15 tilt-rotor research aircraft with a high degree of confidence.

The paper by L.G. Schroers[18] (AVRADCOM, US) examines the predicted aeroelastic characteristics of the XV-15 aircraft in the light of the major parameters effecting rotor-pylon-wing stability, describes the flight test techniques used to obtain XV-15 aeroelastic stability, and compares the flight test results with predictions. It also provides limited correlations (for symmetric wing beam bending mode) of the flight results and analytical predictions against windtunnel tests on a 1/5 scale semi-span wing, full-scale semi-span wing, 1/5 scale aircraft model, and full-scale aircraft. The XV-15 has twin three-bladed propellers (7.6m diam) located at the wing tips and gimbal-mounted to each hub with an elastomeric spring for flapping constraint, being driven by two Lycoming T53 turboshaft engines modified for both vertical and horizontal operation. The flight control system includes an exciter-actuator (1 to 10 Hz) in the right-hand flaperon system to excite the wing beam and torsional symmetric and asymmetric bending modes, plus another in the right-hand collective system to excite the wing chord symmetric and asymmetric bending modes. Flights in moderate turbulence were also used to provide a broad-band excitation force.

The conclusions drawn from the present analysis are that:-

- Within the airspeeds already tested in aeroplane flight, apparently from about 170 kn to 300 kn TAS, the XV-15 is free of structural aeroelastic instabilities.
- Resonant frequencies can be reliably predicted using the NASTRAN method.
- The aeroelastic investigations indicate that the theoretical and model testing methods provide predictions that are in general conservative and adequate for future development of the tilt-rotor concept. However, in respect of the value of the damping ratio for the low frequency wing beam mode, NASA and Bell analytical predictions do differ noticeably towards the higher airspeeds; the former tends to be confirmed by the flight test results and the latter by the relatively optimistic model test results.
- Flight test techniques need to be refined to lower the risk to the aircrew, decrease the time required for data collection, and permit better excitation of selected structural modes; exciters should be installed on both wings and rotors.
- Post flight off-line data analysis method should be refined and, if possible, moved to on-line data processing systems.

Discussion stressed the importance of examining more extensively conditions in the higher-order aeroelastic modes as well as the primary, and also of extending the investigations to higher airspeeds (say, powered dives) where predictions imply that the damping may fall off to zero. The possibility of incorporating active control systems for gust alleviation in future tilt-rotor studies was raised, including feasible governing of rotor rotational speed; the ride quality at low altitudes is already said to be quite good because of the reasonable wing loading (3.7 kN/m^2).

5.2 Structural aspects for variable-sweep combat aircraft

The complex requirements for an all-weather combat aircraft with STOL and supersonic performance and with high manoeuvrability throughout the flight envelope result in an optimal concept, including special features such as a highly loaded variable-sweep wing in combination with sophisticated high-lift, fly-by-wire and automatic terrain following, supersonic engine inlet with variable geometry, and three-spool low-bypass engines with integrated thrust reversers. To accommodate all these features in a minimum size/weight aircraft, special attention to the structural aspects is essential and extremely involved. The paper by K. Knauer[19A] (MBB, GE) describes relevant ground-based and flight techniques used for proof of structural integrity and certification of the Tornado multi-role combat aircraft, developed jointly since 1970 by MBB (GE), B.Ae. (UK) and Aeritalia (IT) and of which over 150 are already in service. Only a few aspects of this comprehensive paper can be recalled here.

As regards load analysis and tests, in most cases the structural integrity is demonstrated successfully by the ground test programme, where component and element tests define or verify the allowed basic components, while major static and fatigue tests demonstrate that the aircraft is adequate for different design load conditions. However, the selection of these design load conditions is a complicated and risky iterative process, which has to show that in the whole Mach-altitude-manoeuvre envelope no additional design conditions (beyond those already considered) are likely to be expected. This is done by using progressively refined rational mathematical models representing the aerodynamic, inertial and dynamic behaviour, of the whole aircraft (including flight control and actuator systems) to simulate c.g. responses in design-critical flight and ground manoeuvres, and of the major aircraft components to cover their design loadings during this manoeuvring plus in special cases their reaction on c.g. response (hinge moment and component dynamics). This matching of mathematical models for advanced high performance aircraft naturally starts with the update of theoretical aerodynamic data by means of windtunnel test results; pressure-plotting models prove to be a relatively reliable means for covering the aerodynamic loading of major aircraft components - with rigid unbent and bent wings representing 1g and high-g condition. However, such windtunnel or analytical predictions still can yield errors because of uncertainties or unconsidered effects, especially in the transonic regimes. Therefore a comprehensive flight load survey was planned as an integral part of the design and development of the Tornado and was performed on two prototypes, one with its instrumentation tailored separately for the clean-aircraft load survey and the other for the store loads measurement task, as discussed later.

The Tornado undercarriage design was performed according to a particular specification and, after rig testing (drop testing, strength test, etc), the undercarriage was cleared for prototype flying. But flight trials revealed unsatisfactory torsional stiffness of the main undercarriage. This problem was solved mainly by stiffening the torque links in combination with the introduction of a slight wheel toe-in and a re-adjustment of the hydraulic damping. Additionally the nose gear airspring was modified in order to cover unexpected loads from the thrust reverser operation.

Verification of the fatigue life of the structure is of course of great importance for modern fighter aircraft, where the number of missions and provable life hours is considerably less than for commercial aircraft, but the number of load cycles per flight hour and the severity of the spectrum is considerably higher. The basic design requirement for the Tornado structure was a pure fatigue life demonstration up to four times of the operational life, with the basic load spectrum defined by the customer by extrapolation from international experience of fighter aircraft. A full-scale hinge fatigue test to demonstrate the fatigue behaviour of the most essential section of the Tornado structure was important at an early programme stage. The major airframe fatigue test giving the final fatigue life proof for Tornado is also unique in its extent with respect to the loading system and loading programme, with 16000 flight hours simulated on the test to validate 4000 safe airframe life. Fatigue life monitoring for Tornado is also being incorporated; firstly by installing g-counters in each aircraft and registering selected aircraft flight conditions on a data sheet; and subsequently by installing a statistically representative number of 'maintenance recorders', in order to improve the accuracy of the residual fatigue life prediction and to increase the structural area for fatigue prediction and to measure the structural area for fatigue life monitoring.

The role of structural dynamics in the design process has also become much more important with the increased emphasis towards high-performance multi-purpose aircraft. Parameters that improve performance characteristics such as lower thickness/chord ratio, larger surface areas and higher aspect-ratios are driven to near optimum values; within the constraints of weight and structural dynamics limitations such as flutter, vibration and acoustic environment, control surface effectiveness and buffet response. Because the Tornado features a powerful fly-by 'Command-and-Stability-Augmentation-System', aeroservoelastic analysis and tests had to be performed to avoid adverse coupling of this CSAS with the structure. The aircraft also carries a tremendous number of external stores on two underwing pylons on each side and on the fuselage, differing in weight and radius-of-gyration. So the problem of giving flutter clearances as discussed later must be tackled with very careful selection of certain stores for each wing sweep, to be able to read across to other stores. The problem becomes aggravated when tanks are considered and flutter-free fuel-emptying sequences have to be defined. More widely, in considering structural dynamics, covering the supersonic flight regime almost doubles the analytical and test efforts compared with subsonic aeroplanes.

For engine air-intake load assessment, the occurrence of engine surges must be considered, arising as a sudden reduction in flow in the compressor caused by an abrupt flow breakdown or aerodynamic stalling of the blades in a portion of the compressor. This sudden reduction in flow creates a strong shock wave which moves upstream of the intake duct, leading to high peak pressures and so-called Hammershock induced loads in the intake, in addition to the steady-state pressure under running conditions. Although a dynamic test would offer the best possibility to accomplish a realistic loads assessment for all components of the air intake which comprises a 3-ramp arrangement for the Tornado propulsion system, such a dynamic test is not feasible. Therefore a number of theoretical investigations had to be established and static tests of critical parts of the structure were carried out using the calculated loads[19A].

Since the FMP 1975 Symposium (Valloire), an extensive programme of flight load measurements have been made on the Tornado aircraft to contribute to service clearance as required by the American Mil. Spec. The paper by J.R.J. Dovey[19B] (B.Ae., UK) reviews the purpose of flight load measurements, the overall load measurement programme, the calibration of the load measurement devices, the data reduction facilities, the flying techniques and the methods used for detailed analysis of results. Comparisons are made between flight measurements and predictions for several aircraft components, for specific manoeuvres and for rates of change of load with change of aircraft parameters. The contribution of flight load measurements to the extension of the flight envelope in rapid roll manoeuvres is discussed, and the usefulness to the final Tornado flight clearance is also assessed.

The extensive analysis[19B] demonstrates that the flight load measurements have certainly made a significant contribution to the Tornado service clearance and expansion of the flight envelope, with a greater assurance of safety than would otherwise have been the case. Naturally, care is needed in defining the instrumentation, gauge positioning to ensure linear responses, and avoiding extraneous effects. Adequate calibration of strain-gauges must be provided, including in-flight datum and calibration checks. Also, adequate facilities must be provided to allow monitoring, easy data acquisition, storage and retrieval, and to carry out detailed analysis. Overall, the flight programme must cover a broad distribution of flight conditions in addition to areas where critical cases are predicted to occur.

In the linear range of load measurements for the clean aircraft, flight results have generally been in close agreement with predictions. However, in some instances, for example taileron torque, windtunnel data has been found to be unreliable; possibly due to inadequacy in the measurement techniques, Reynold number deficiencies, or aeroelastic effects. In such circumstances theoretical methods grossly underestimate the loads. Again, for transonic conditions, where theoretical methods were not available, the windtunnel data were found to be inadequate, leading to greater wing and rear fuselage loads in flight than those predicted. As regards wing aerodynamic behaviour in the manoeuvre flap configuration at high incidence, small differences between windtunnel and flight were sufficiently great to make a significant difference to the flight envelope cleared. Moreover, noticeably lower values were achieved in flight (at moderate to high incidences) for wing bending moment due to incidence and wing bending moment due to roll rate, these differences being associated with the development of shocks as transonic conditions are encountered; this results in smaller loads which allow clearance to a larger flight envelope than predicted.

Thus, within the context of the minimum weight philosophy and hence untoleranced loads used for Tornado design, the flight measurements have been shown to be an essential means to establish flight clearance, since some measured loads were found to be different from prediction. More generally, careful consideration should be given to the need for comprehensive flight load measurements based on the requirements of the particular project. The magnitude of the wing loading affects the extent to which prediction and flight are likely to disagree, while tolerances on prediction may result in acceptable weight penalties dependent on the requirement of the particular aircraft. In this respect, it is worth recalling that the g-loading for complex combat aircraft such as the Tornado is several times that for civil airliners, so that combat design loads occur almost exclusively in conditions of non-linearity of the aerodynamic characteristics resulting from flow breakdown, shock separation, etc.

5.3 Flight flutter testing, analysis and active suppression

During the development of commercial or military aircraft, it is standard practice to perform flight flutter tests to show that the aircraft is free of flutter within its flight envelope, the frequency and damping of the appropriate flight vibration degrees of freedom being measured for various speeds and Mach numbers. This is usually done by installing transducers, such as accelerometers, gyros, potentiometers, goniometers and strain-gauges at various points on the aircraft; then inducing vibrations in the airframe by various natural or artificial means; and recording the resulting oscillation amplitudes and phase relations. The data are recorded on magnetic tape onboard the aircraft or transmitted by telemetry (pulse code modulation) to ground recording equipment, or both.

The paper by H. Zimmerman[21] (VFW,GE) and R. Destuynder (ONERA,FR) usefully first reviews the major flight excitation systems developed and used in the past twenty years, by atmospheric turbulence, available control surfaces, 'bonkers', inertial shakers, and vane excitation systems. The excitation process may therefore be harmonic, impulsive or random depending on the particular system, and where possible the excitation force is also recorded and processed. The data are usually filtered, digitised and transmitted to a ground-based computer, which calculates power spectra, correlation, coherence and transfer functions, if possible. By matching these functions to appropriate mathematical models, the frequency and damping of each mode may be obtained. Flight flutter tests are usually carried out by advancing flight speed and Mach number in discrete authorised steps, so the quick-look qualifying capability of telemetry at each step has become a valuable guidance and safety tool in flight flutter testing.

The recent developments of the vane excitation system in both the USA and Europe are attractive in that, by proper design, the following characteristics can be realised:-

- The elasto-dynamic behaviour of the aircraft is not altered by the vane installation, except for its additional masses.
- The excitation forces are well-defined and can be measured and controlled easily, and also correlated with the induced vibration.
- If the vane chord is much smaller than the aircraft surface under primary investigation (eg the wing), then the 'reduced frequency' of the vane is correspondingly smaller, which makes the unsteady airforces practically constant over the range of aircraft frequencies.
- Undesirable moment and force reactions can be reduced by vane mass-balanced design and a suitable choice of the torque motor axis location near the vane aerodynamic centre.

The tip-vane excitation system developed for the flight vibration tests of the Airbus A.310 transport aircraft is described in detail by Ref.21, and is reported to have been extremely successful. Discussion implied that the possible application of such a powered tip-vane system for flutter alleviation is unlikely to be acceptable for civil airline operation.

The large variety of external stores carried on underwing pylons of modern combat aircraft requires a large amount of prediction work to assess the flutter behaviour at the early development stages of the aircraft. Such work based on theoretical calculations, windtunnel model experiments and aircraft ground-resonance testing, for configurations both without and with stores attached, has to be matched with flight test data on key configurations without and with stores to achieve final qualification. The paper by G.D. Ferrari[19C] (Aeritalia, IT), A. Lotze (MBB,GE) and R. Pyrah (B.Ae., UK) discusses the problems the dynamicists had to face in correlating flight results with analytical predictions during the final flight test period of a variable sweep aircraft (Tornado), particularly with underwing stores.

The problem of structural non-linearities raises two fundamental aspects; firstly, the interpretation of flutter flight test results implies an assessment of the degree of non-linearity in the behaviour of flying prototypes during individual measurements; secondly, the prediction of production aircraft non-linear behaviour is required during all service life, in which any inspection or replacement of parts must be kept to a minimum. The variable-sweep underwing-pylon alignment system can lead to two different kinematic behaviours, one with the pylon effectively clamped to the wing by static friction in the pivot bearings (yaw loads transmitted to the wing itself), or the other with the pylon free to rotate relative to the wing (yaw moment transmitted to the 'elastic' control rod).

As regards excitation techniques, both inertia exciter and 'bonker' excitation (rocket motors) were discarded since, with the low wing-store frequencies expected for this aircraft, high energy levels would be required which would entail fairly large and massive installations affecting the flutter characteristics under investigation. Turbulence as a means of excitation was similarly rejected, since levels encountered were not expected to be sufficient to obtain the elastic control rod kinematic conditions. In view of the number of stores to be cleared, a dedicated flutter store was developed from an underwing fuel tank, with hydraulically operated vanes providing the excitation force; and with variable ballast masses to stimulate the mass, centre-of-gravity and radius-of-gyration of the critical stores to be cleared. The principal excitation then used was frequency sweep with facility for varying the excitation amplitude, the responses of the aircraft and stores then being measured by multiple accelerometers. These results were analysed by computer programs on Fourier Analyser (HP 545 IC), and were supplemented by manual analysis of the response due to stick jerks and to wing sweep start-and-stop inputs.

Another important problem arises with modern aircraft using sophisticated power controls and automatic control systems, which are basically designed to manoeuvre the aircraft and to provide sufficient damping for the rigid body modes. Thus, since the sensors are in practice attached to a flexible structure, motions of the elastic aircraft are also picked up and may be modified by the system. It is necessary therefore to provide an analytical approach for the complete system, including unsteady aerodynamic forces and elastic structure modes, to predict the response of the aeroplane with the control system and to correlate with test data. For the Tornado, a special analysis was made of evident stick pitch coupling with structural modes, making use of supplementary ground testing and flight flutter testing.

The influence of transonic aerodynamics on store flutter presents an especially difficult problem predictions being hardly possible if no transonic flutter model nor unsteady pressure distribution model is available. Evidence is presented that there is a pronounced transonic effect on the damping of the wing bending mode, increasing with Mach number and with incidence, but generating an instability only at very high non-realistic speeds. Another possible reduction of wing bending damping capable of adding to the attenuating effect of transonic aerodynamics was found to be generated by non-linear structural behaviour and apparently was produced by the coupling between the store-yaw and wing-bending modes.

It is argued that flutter clearance cannot yet be based exclusively on flight testing nor on conventional flutter calculations, especially with nonlinearities generated either by structural, control-system or aerodynamic transonic effects[19C]. Flutter flight testing is a useful and required tool for flight clearance purposes; but, approaching areas with low flutter margins, good correlation with analytical investigations confirmed by ground resonance tests is vitally necessary, in order to be able to explain the physical behaviour of the flutter case and to avoid unsafe conditions during flutter flight testing. If correlation between flight test and analytical prediction is poor, possible non-linear effects must be incorporated in the analysis. Having finally proven good correlation with flight testing for special test conditions, the clearance according to the most critical case during the whole service life and considering all possible amplitudes has to be provided by analysis, if this condition cannot be reached by flight testing.

Clearly, the correlation of theoretical predictions and experimental flight-test results of aeroelastic effects in the high-subsonic to transonic speed range is of great importance because aeroelastic effects frequently are critical there in aircraft design. An objective of NASA's drones for aerodynamic and structural testing programme (DAST) is to pursue investigations within this speed range, using a series of aeroelastic research wings (ARW) which will be flight tested in combination with a modified Firebee II target drone vehicle fuselage utilising the remotely piloted research vehicle technique (RPRV). The paper by G.B. Gilyard[20] (NASA, US) presents the flight flutter test procedure and results for the first aeroelastic research wing (ARW-1). The primary research objective of the ARW-1 is to investigate systems synthesis and analysis techniques applicable to active control of flutter, using an onboard analogue flutter suppression system (FSS). A secondary objective is to use flight test to validate analysis techniques for aerodynamic loads predictions. The use of the RPRV poses special considerations in the conduct of the flight testing, because test time per flight is quite limited and a higher probability of vehicle loss can be an accepted risk.

The ARW-1 is a swept back transport-type wing of 6.8 aspect-ratio and of supercritical aerofoil shape, with supercritical design point at M=0.98 and height 13.7km, though the active flutter suppression goal of 20% increase over the unaugmented flutter speed was to be accomplished at heights of only 3.0 to 4.6km. The flutter-suppression function was performed for both symmetrical and anti-symmetrical flutter modes by control of the wing ailerons by hydraulic actuators, implemented from accelerometer measurements of left and right wing tip accelerations. All onboard data measurements were telemetered to the ground via pulse-code-modulation systems, the critical flutter parameters such as accelerations, aileron deflections, excitation signal and servo-commands being transmitted at a maximum rate of 500 sps with pre-filtering to prevent aliasing. The remaining primary system paremeters consisted of 46 signals from a standard flight-test instrumentation line-up, while a secondary system monitored wing-load distribution sensors comprising 86 surface static-pressure sensors and 16 strain-gauges.

Real-time analysis of fast frequency aileron excitation sweeps provided reliable damping estimates, the open-loop flutter boundary was welldefined at two altitudes, a maximum Mach number of 0.91 was obtained; both open-loop and closed-loop data have been of exceptionally high quality. Nyquist analyses of sweep manoeuvres appear to provide additional valuable information about flutter suppression system operation, both in terms of phase-margin estimates and as a means of evaluating manoeuvre quality. Although the FSS system provided augmented damping at speeds below the flutter boundary, an error in the system implementation caused the wing to be unstable at lower Mach numbers then anticipated, and the vehicle experienced close-loop flutter on its third flight. The vehicle has been rebuilt, real-time flutter testing procedures have been improved and further research tests are scheduled for late 1982.

5.4 Structural design status

The following brief appraisal of structural design capabilities and prospects, particularly in respect of aeroelastic aspects, is based mainly on the assessment provided by A. Filisetti (Aeritalia, IT) during the round-table discussion. There is already in principle a capability to develop an aircraft to the limits of its true flight envelope with no margins left and no associated penalties. This may be accomplished through a process of theoretical prediction, ground-based tests (windtunnel, static-rig, ground-resonance and load calibration), and flight trials. Mathematical reference models are used throughout, from initial prediction all the way up to extrapolation of flight test results, with the models being updated by matching the experimental results, as already discussed earlier in relation to aerodynamic performance. Steady and dynamic loads, stresses and flutter analysis can follow profitably from this technique. A useful example has already been given for rapid-roll testing in flight, where interpretation of early results is done by matching the mathematical model with them, to facilitate the subsequent flight predictions. The prediction capability in respect of the aeroelastic stability of a tilt-rotor is especially encouraging.

Major shortcomings which appear to exist may be recalled as:-

- Poor reliability of prediction of structural loads in transonic region, particularly because of Reynolds number effects and structural deformations.
- Difficulty in flutter analysis to account for non-linearities, both structural (friction, free-play) and aerodynamic (Mach and incidence effect).
- Inadequate interpretation of flutter flight tests in critical conditions.
- Unsatisfactory integration in the flutter analysis of control system characteristics.

Naturally, relevant improvements in analysis and test methods must be undertaken, taking advantage of current and future-generation electronic-computer capabilities, but in all cases experienced engineering judgement remains a basic requirement.

Future operational requirements for military aircraft and associated technical advances will demand the design of new weapons systems by an integrated approach, as illustrated by the following examples. The speed and manoeuvre performance of an interceptor and the radar detection performance must be defined in connection with the range of the SR missiles to maximise combat effectiveness. The weapon and propulsion control systems will be integrated in the flight control system to improve survivability and to reduce pilot workload. Active control technology will alleviate the conventional requirements for aerodynamic design (relaxed stability) and structural design (load alleviation, flutter suppression, etc.), reducing weight and cost of the aircraft, or permitting higher performance levels. Moreover, cross-feeding of the new technologies offers an outstanding way towards improvements in cost-effectiveness.

Having set general requirements, the structural design of a new aircraft must follow an automatic iteration process on a computer, taking the sequential steps of load analysis, stressing, weight and stiffness calculations, aeroelastic deformations, aeroelastic loads; all with the constraints of flutter and steady aeroelastic requirements. The problems are now aggravated by the fact that we have to cope with new kinds of structures made of advanced composite materials, effectively commensurate with a technological jump in structural design and manufacturing techniques. The new composite structures are characterised by high specific resistant anisotropic material, facilitating tailoring to the load path with a potential saving in weight and cost of about 25% to 30%. At the outset, the design criteria must really take into account the manufacturing techniques, the possibility to qualify hybrid structures, the non-destructive test methods, the allowable loads defined by the non-linearity of the strain versus stress and by the hot and wet conditions which could be quite severe in a supersonic combat aircraft. There is therefore plenty of work to be done in order to effectively exploit the new materials, requiring of course application of modern structural optimisation techniques.

6. Subsystem Performance

6.1 Store release characteristics

The integrated development of modern combat aircraft, with particular reference to the capability of carrying and delivering a large range of external stores, has led to extensive requirements for the investigation and reliable prediction of safe separation of the stores and weapons from the aircraft; compatible with ensuring release accuracy for operational delivery requirements which, of course, bring in a wider range of store trajectory parameters. Purely theoretical methods are not considered adequate for store load estimation, particularly since non-linear effects due to flow separation at incidence are needed for most calculations. Windtunnel tests are usually accepted as the most reliable source for trajectory calculations, especially if used to validate a mathematical framework; while such tests are deemed essential prior to flight release, despite some remaining doubts on tunnel model testing techniques and similarity considerations. Again, it can also be argued that some theoretical predictions are essential to modify tunnel model results, for example to introduce the effects of the manoeuvring load factor at the store ejection points and to ensure correct correlation between flight Mach and Froude numbers.

The paper by F. Porrato[22] (Aeritalia, IT) describes an integrated methodology for the evaluation of the separation characteristics of external stores from the parent aircraft, based on a combination of mathematical models, tunnel tests, ground and flight trials. Three successive phases are employed which can ensure not only safe jettison of stores, but also predict profitable modifications of the aircraft/store interface and early optimisation of store release sequence. Investigations have naturally been focussed around the MRCA Tornado project. First a mathematical framework is built up by dividing the aerodynamic flow region for the separation trajectory into an interference field close to the aircraft where there is mutual interference between the stores themselves and the aircraft, a near-field from about 1 metre downwards below the aircraft where the flow field is disturbed only by the presence of the aircraft (no mutual store interactions), and a far-field from about 5 metres downwards where free-stream conditions sensibly exist. All available input data is fed into the main computer program which essentially solves the store motion equations, including sub-routines to define store aerodynamic/inertial characteristics, ejection rack performances, aircraft flow field, etc. Predictions are then made for tunnel-model dynamically-scaled store-jettison tests carried out on the specific aircraft configurations of interest, the primary aim being to gain a better insight into the store separation behaviour and to obtain some datum experimental results with which to 'adjust' the mathematical model.

The second phase comprises specific flight trials, with store behaviour recording by onboard cameras and ground kine-theodolites, permitting evaluation of all six ballistic components against time. Detailed analysis of the deviations between the experimental and theoretically-predicted trajectories then allows identification of which input data of the mathematical model have to be modified, with an iterative loop to achieve good agreement between the two trajectories. Further flight tests, analysis and matching are undertaken and continued until the mathematical model is adequately validated throughout the designated flight-test jettison envelope. During a third phase, this flight-envelope is theoretically extrapolated, by means of the determined mathematical model, to clear the envelope requested by a particular customer or to specify the envelope boundaries within which safe store separation can be guaranteed. Such developments over the past decade now allow essential flight-trial requirements in respect of store separation to be reduced substantially, to about half of what would otherwise be required with modern combat aircraft. Future extension of this methodology towards improving also ground-delivery prediction accuracy now seems worthwhile.

Some comments made by A.F. Darroch[24] (B.Ae., UK) and others imply that improvement of store-release predictions requires the incorporation of the following developments:-

- Non-linear effects, viscosity effects, and possibly unsteady flow considerations in theoretical methods, so that they can be used with greater confidence in a typical store release environment.
- Supersonic and transonic flow theoretical treatments for off-body flow-field predictions and mutual interference effects.
- Windtunnel techniques for accurate and repeatable jettison testing and simulated gravity.
- Increased accuracy of in-flight trajectory recording and real-time transfer of recorded trajectory to the ground.
- Faster and more accurate trajectory analysis to complement real-time transfer of recording and to allow possibility of multiple releases in one flight with clearance for envelope expansion between releases.
- Reduction of scatter in ERU performance and better definition of aircraft structural flexibility effects.

As regards relevant interests of the AGARD Fluid Dynamics Panel, C. Bore (B.Ae., UK) recalled his proposal that a Symposium is now needed to cover the aerodynamic consequences and release of external stores; including drag, installed airloads, local buffeting, lift and stability effects, released trajectory and associated prediction and measurement techniques.

6.2 Helicopter engine air inlets

From the introduction of turbine-engines instead of piston-engines as helicopter powerplants some 25 years ago, with the subsequent doubling of cruise speeds since then and the enormous rise in fuel costs over the past decade, considerable research on engine air inlet design has been essential to improve propulsive efficiency and to preclude engine surge conditions. The paper by F. Toulmay[23] (Aerospatiale, FR) describes the methods established at Aerospatiale over the past five years for the design and development of air inlets. The major inlet design problems to be solved relate to pressure loss, dynamic pressure recovery, pressure distortion, hot air re-ingestion, compatibility with FOD/Sand icing protection, external drag and other design constraints associated with engine or airframe configurations. Windtunnel testing of scaled models has been found to be the most powerful and flexible tool for solving such problems in the long iterative design process leading from the first project drawings to certification. The selection of principal model parameters for similarity with full-scale, the particular test procedures, including extensive pressure-rake measurements and the facility for real-time processing are especially of interest. Of course some technique problems remain of concern and need to be resolved, including considerations associated with the low Reynolds number and low Mach number plus the high turbulence levels in the Marignane tunnel, and others for proper representation of inlet surface and grill.

The introduction of micro-processors into the tunnel testing procedures for the rapid acquisition and reduction of data has radically reduced delays in the exploitation of such data for direct assessment of installed engine performance and comparisons with flight test results. Overall, available flight results confirm the improvements predicted by tunnel testing, but the results valid for strictly comparable configurations in flight and tunnel only represent a small proportion of the total work carried out. Typical improvements achieved in performance by these means over the past few years, as measured in tunnels and confirmed in flight, include some 8% and 3% gain in hover power for the SA 365C and N respectively, reduction in inlet flow distortion by a factor of 3 for SA 365 N, and 10% reduction of fuselage drag for AS 332. Moreover, it is suggested that forthcoming efforts will reduce hover power losses by at least 1.5%, while giving a 2% improvement of dynamic pressure recovery in cruise.

Discussion suggests that some apparent deficiencies noted in the prediction of engine surge conditions for flight could have arisen because the tunnel model measurements related only to steady-state distortions, since, in view of the low Reynolds number of the tunnel models, dynamic distortion measurements have often only been considered worthwhile in flight testing. As regards engine-compressor stall, altitude effects are currently only given qualitatively by trend data; additionally, for rearward flight conditions, no analytical techniques are available[24]. Unfortunately, there was no discussion of the possibilities of relevant tunnel testing at correct Re and M, either at full-scale in larger atmospheric tunnels or at about one-third scale in the new pressurised tunnels.

7. Conclusions

7.1 General

The following general comments are offered in respect of the overall significance of the presentations, discussions and questionnaire responses as regards the progress made since the first FMP Symposium (1975) on ground/flight testing techniques and prediction/correlation capabilities, together with the implications as regards required improvements and research needs. The Symposium noted that there have indeed been major improvements in prediction capabilities in the last decade; enhanced by large advances in test instrumentation and data processing for windtunnel and flight analysis/correlation, in new windtunnels (both Europe and North America), in flight test techniques and measurement accuracy, and in computational treatment of theoretical aerodynamics. However, despite all these improvements and the development of computational aerodynamics towards providing an efficient design tool, there are still problems in providing accurate and adequate performance predictions. Likewise, in respect of prediction of flying qualities, advances in both ground-based and airborne simulators have continued, but the inclusion of realistic non-linear mathematical models (aerodynamic, aeroelastic, control) and of representative subjective cues to the pilot still presents problems. To minimise errors in prediction of flight performance and handling, the individual prediction tools (Fig.1) must be continually revised and employed as complementary techniques, naturally with a cost-effective bias in their combination according to their individual advantages and disadvantages for the specific need and at the particular time.

More generally, the experience gained in the development of specific civil and military aircraft programmes over this time-period and their presentation at AGARD Symposia, Lecture Series, etc., was acknowledged as a continuing source of important technological enrichment for the NATO countries and as a significant aid towards better products and increased efficiency in aerospace development. The pay-offs from our sophisticated windtunnels, super-computers, elaborate flight-testing, and complex flight simulators will be severely handicapped unless the engineers and scientists employing them are of the right calibre, have adequate training/experience in the relevant disciplines, and have a real interest in the integrated application of the available tools and disciplines for improved prediction and design of aircraft capabilities. Concern was particularly expressed that, with the increased sophistication of testing, computational and prediction techniques, engineers may lose track of the physics and real purpose of prediction and comparison. The need for continual direct communication between flight, windtunnel, theoretical and design personnel remains as important as ever.

More specific conclusions are next divided conveniently into those directly associated with facilities and testing techniques, and others concerned with specific prediction capabilities. Here I would express my appreciation again to the Contributors and their Establishments, not only for their Symposium papers and discussions, but also for their cooperation in preparing the many responses to the FMP Questionnaire and some aide-memoires on their round-table comments. Additionally, I would apologise if, for conciseness or lacking adequate time to check with particular originators, I may have unwittingly omitted or misrepresented any major opinions or essential arguments.

7.2 Facilities and testing techniques

1) In the area of instrumentation/measurement and of data processing techniques for windtunnel and flight experiments, large advances have been made providing better confidence in the attained data and consequently improved comparison bases. Now, wider appreciation and use must be encouraged of 'parameter identification techniques' in tunnels as well as in flight, but at the same time further improvements must be sought in our physical understanding and thereby in the mathematical frameworks for the analysis of particular experimental data, including linear and non-linear treatments.

2) The provision of new or improved windtunnels in Europe and North America, particularly at subsonic and transonic speeds, has significantly enhanced the aircraft prediction capabilities of the aeronautical industry; while the forthcoming developments in respect of practical cryogenic tunnels for higher Reynolds numbers and of

adaptable-wall tunnels for minimisation of tunnel-wall constraints are eagerly awaited. Experience concerning the working relations between customer needs and test improvements has confirmed that relevant on-going improvements make up an essential basic aspect of tunnel work, which must be strongly supported by and integrated with computer programs. Cost-reduction for complete model testing over the flight-envelope can now be achieved by incorporating faster data collection and analysis procedures on-line, with continuously variable model conditions, to obtain only the essential 'flight' information (eg trimmed polars) suitable for specific design calculations. Nevertheless, the importance of supplementary detailed parameter-variation studies (full data matrices) on complete models as well as partial models must be stressed, for proper aerodynamic appreciation and construction of wider analytical frameworks.

3) Propulsor representation at model scale (flow and geometry) has become even more important in relation to engine/airframe interference considerations for both performance and S & C investigations. Much better simulation of intake-flow, efflux momentum and engine-nacelle shape is fortunately achievable by the continuing developments of air-driven TPS model units; now available at up to 1/6 scale for representation of large turbo-fan engines. For turbo-engine propellers or rotors, electrically driven power units are more practicable and preferable, because their quietness makes them also suitable for propeller/rotor noise studies. In most experiments, measurements of nacelle/shaft axial-force and possibly normal force are required to supplement those of aircraft-model forces and propulsor-shaft torque.

4) Improved ground-proximity representation in windtunnels has become especially important not only for STOL powered-lift operation but even for CTOL conventional aircraft, because practical $C_{L_{max}}$ values between 3.5 and 4.0 are now being attained rather than of 2.0 to 2.5 twenty years ago. Ground-roll, lift-off/first-segment climb, landing-flare/touchdown are all ground effect conditions of considerable concern, where rearward translation of the ground-plane at the correct relative speed (moving-belt) becomes important with the fixed model in the tunnel. For future dynamic descent or ascent conditions, the influence of vertical motion of the model in ground proximity also needs to be checked, since the effective model aerodynamic incidence is affected by the motion even without change in ground attitude.

5) The substantial developments in flight test techniques and measurement accuracy have expedited a considerable advancement of quantitative data collection (rather than qualitative), constituting an integral aide to predictions for new aircraft. Nevertheless, for correlation with ground-based studies, better flight measurements are still required, not only of the detailed aerodynamic loading and drag components full-scale, but also of airframe deformations and propulsor flow characteristics under specific flight conditions. An especially careful accounting procedure must be followed and declared for comparisons of thrust and drag predictions with flight measurements, with the ability of isolating and identifying a variety of important force elements.

6) In computational fluid dynamics very large advances have been possible, primarily because of the *tremendous* developments in electronic computer technology (hardware and software). Even more complex applications of previously intractable theoretical models can now be *envisaged over the next* two decades. These will demand further increases in computer storage by an order of magnitude, further improvements in display/interpretation capabilities, and greater on-line flexibility for program modifications. Additionally, available mathematical algorithms are still quite inadequate to represent many types of aircraft aerodynamics; involving for example airframe turbulent flows, mixed high-speed flows, complex flow separations and component interactions, so that tunnels/flight investigations will there remain predominant for at least the next decade.

7) Free-Flight model techniques have been widely exploited over the last decade, particularly for the examination of handling qualities, covering stability and control near 1-g flight, manoeuvre limitations, spin characteristics, relaxed levels of stability, and active control systems. The different techniques under continuing development include the following, broadly listed in order of increasing cost and lengthening time-scale: flying models in vertical (spin) or horizontal (conventional) windtunnels, free-flight drop-models (from helicopter), remotely-piloted models, and large-scale piloted vehicles with artificially variable stability and control characteristics. Such investigations should of course be integrated not only with ground-based simulators, but also with exploitation of dynamic force measurements in the new high Reynolds number tunnels.

8) Ground-based simulation for flying qualities prediction essentially fills the gap between analytical estimates and flight testing, effectively combining several theoretical and experimental techniques. Its main advantages are the introduction of human-factor elements early in the aircraft/subsystem design phase, effectiveness in uncovering technical discipline interactions and system integration problems, possible real-time simulations with man-in-the-loop involvement, and practical safe explorations of high-risk in-flight conditions. Its primary disadvantages are its basic reliance on a good mathematical model and reliable data input, and perceptual limits in visual and motion cues which can lead to loss of fidelity and misleading confidence; computational and transport lags can also introduce unrealistic dynamic effects. Continual updating of the validation and limits of particular simulators is needed in the light of on-going flight test results, together with continual development of computer graphics for visual displays. Complex full-mission simulators are expensive and can become work-saturated, so part-task simulations or other prediction techniques are worthwhile as a back-up or for lower priority work.

9) In-flight simulation can provide of course a 'real-world' environment for man-machine interface predictions, is still the best validation for high-pilot-gain tasks such as landing, and is valuable as a final proof-of-concept before flight. The disadvantages are that it is usually expensive, is again only as good as the inbuilt mathematical models of the aerodynamics and flight control system (i.e. supporting prediction schemes), and may be limited in ability to simulate all important aspects of flight (e.g. visibility, side-force).

10) Flight test techniques have become vastly more sophisticated, so that dynamic manoeuvres are now performed even to gather performance data rapidly, much more data is gathered per flying hour with the greatly improved instrumentation and systems, and the data repeatibility is much better. With the advent of the better instrumentation, high capacity computers, and powerful software tools including parameter identification techniques, the stability-and-control derivatives as well as performance data can now be routinely extracted from flight test data, and non-linear effects more readily quantified. This in turn allows more confident

application of ground-based simulators and thereby earlier support of aircraft handling qualities tests in areas of high hazard. Nevertheless, this is an expensive and time-consuming technique, while there can remain real difficulties in obtaining accuracy and conditions relatable to a useful mathematical model. So such work requires concentration on obtaining reliable meaningful results, with adequate checking and evaluation of onboard instrumentation and software.

7.3 Specific prediction capabilities

(1) Ground-based prediction techniques (windtunnel and analytical) are still often subjected to unconstructive criticism, when there is apparently poor correlation with extracted flight-test results from real aircraft. Nevertheless, the ground-based modelling and test limitations (experimental or computational) are usually declared and often quantitatively expressed. In contrast, the likely deficiencies of the flight test techniques and more variable test environment are sometimes conveniently overlooked, especially in respect of the real measurement accuracy of the on-board instrumentation and the adequacy of the aero-mathematical modelling of the aircraft and its flight behaviour, for meaningful interpretation and application of the flight test data. With the increased employment of system and parameter identification concepts, particularly for extreme conditions of the flight regime, the physical appreciation and error assessment for such possible deficiencies become of equal importance to those for the limitations in ground-based techniques. Finally, it should be more widely appreciated that there are inherent differences in character and in achievable standards between the techniques for the prediction of flight performance or flight dynamics and those for the prediction of flight critical behaviour such as instabilities or pilot-induced oscillations.

(2) Evidently, for aeroplane performance prediction, no one technique can cover all airframe and engine configurations and all flight regimes. Moreover, most attempts to standardise performance estimation methodologies amongst aircraft manufacturers fail, not only because of natural reluctance to change or disclose in detail preferred domestic methods, but also for lack of adequate proof as to the best methodology combination. Aerodynamic prediction techniques are expectedly the most reliable for efficient en-route flight conditions outside the transonic regime, becoming worse where piloting techniques or flight-regime limits enter as major factors. Specific aerodynamic elements warranting further attention include the following:-

- Drag variation with Mach number and lift coefficient, devoting special attention to the influence of surface condition, joints/gaps and air-leakage.
- Lift and drag variation at high incidence and allied stalling or buffet penetration characteristics, taking into account practical structural deformation.
- Drag creep and divergence prediction by high-speed tunnel testing.
- Engine inlet and exhaust flow interference, especially in relation to spillage-drag and afterbody-drag, along with flow stability needs.
- Mutual interaction between the wing, fuselage, tail-unit and powered-nacelles in combination, especially for the closely-coupled configurations of modern combat aircraft and executive rear-engined transports.
- Excess drag arising from aircraft store installation, partial carriage as well as complete.

(3) The current generation of helicopter airload prediction techniques is especially limited in the ability to extrapolate a given computer program with confidence to new or unrelated designs. While significant advances continue to be made towards understanding and predicting individual aerodynamic characteristics such as rotor-blade behaviour and interference phenomena, proposed sophisticated computer program codes for rotor airload predictions under practical conditions have yet to be validated thoroughly against complete detailed experimental data, which are in themselves difficult to obtain. More generally, helicopter performance prediction methods rely considerably on the preferred modelling of the rotor wake and still require empirical corrections from windtunnel and flight data to help account for rotor wake interference on the pylon/fuselage, auxiliary rotor and any tail-unit. Thus continuing fundamental theoretical and experimental work remains essential to improve the reliability and scope of existing analytical frameworks, and to complement proposed statistical treatments of accumulated data banks from past and future measurements effected in helicopter flight.

(4) As regards flying quality considerations, mathematical modelling techniques to facilitate prediction of aircraft dynamic behaviour and of relevant control system requirements have been extensively developed over the years. But the acquisition of the necessary aerodynamic derivatives and the accurate determination of nonlinear aerodynamic characteristics at high incidence still demands experimental time-dependent measurements in windtunnel and flight, particularly in relation to stall and buffet penetration and to spinning characteristics. Moreover, the greater role that controls now play in aerodynamics, through the integrated incorporation of active control technology, demands not only a greater need to predict the particular control aerodynamic characteristics but also the need for more accurate knowledge and prediction of the other aerodynamic characteristics of the aircraft. The careful application of parameter identification techniques for the meaningful analysis of systematic flight test results becomes especially important here. As for performance considerations, we must likewise improve our physical understanding to ensure a sound basis for formulating the analytical frameworks, even to the extent of testing dedicated windtunnel and mathematical models for this purpose.

(5) The prediction of structural design loads (steady and unsteady aerodynamics) and of aeroelastic behaviour (favourable as well as unfavourable) has become much more important and complex, particularly with the increased emphasis towards high-performance multi-purpose aircraft, while complementary flight load predictions and in-flight load measurements are needed to expedite appreciably the more demanding flight clearance procedures. Analytical shortcomings appear to arise particularly in respect of the following:-

- Detailed predictions of load distributions in the transonic regime.
- Non-linearities (structural and aerodynamic) in flutter analysis, especially important as regards interpretation of critical high-g conditions.
- The complex integration of active control system characteristics in aeroelastic studies.
- The recent technological jump in structural design (with composite materials) and in manufacturing techniques.
- The possible large loading variations from installed stores over the flight envelope and in different operational usage.

- The tendency towards a minimum aircraft weight philosophy with untoleranced load limits.
- The need to predict operational boundaries more accurately and possible pilot-induced oscillations, for highly-loaded flexible aircraft.

(6) For the evaluation of external store release characteristics from modern combat aircraft, an integrated methodology is essential involving a specially developed combination of mathematical models, windtunnel tests and flight trials; for example along the lines outlined in Section 6.1. Thereby, besides the substantial savings in the number of flight trials and in the time to provide safety clearance, a thorough knowledge of the various factors governing the separation paths of different stores can be achieved and from that the background for further developments. New improvements to the different techniques contributing to such integrated methodology for store separation prediction are both justified and feasible, along with possible extension also to prediction of the achievable trajectory to the target.

(7) For solving problems associated with helicopter engine air-inlet design and performance prediction, windtunnel testing of scaled models has been developed into a very powerful and flexible tool, taking advantage of micro-processors for the rapid acquisition and reduction of pressure-rake data. Some differences between tunnel model-scale and flight full-scale results may well be due to the low Reynolds and Mach numbers of the particular tunnels employed, so that application of existing larger (or pressurised) tunnels with higher top speeds and possibly lower turbulence levels should be encouraged. For investigation of potential engine surge conditions, more measurements of unsteady flow distortions (as well as steady) should be made on models.

(8) Aircraft noise/vibration now presents an inherent prediction problem in aircraft flight performance and dynamics, but regrettably no specific paper was presented at this Symposium. Externally propagated noise can cause not only civil annoyance at ground-level, but can also promote the military risks of early acoustic detection - particularly if the radar, infra-red and visual signature have been reduced already. Internal noise and high-frequency vibration is important in both civil and military operations from ride-comfort and communication aspects, while also affecting flight operational effectiveness in respect of aircraft combat and weapon/store delivery.

8. Recommendations

The critical comments in the extensive Conclusions and in the Main Text already imply some recommendations for specialist research and development over this wide scientific and technical field; covering techniques for the prediction of aircraft performance, dynamics, aeroelastics and store behaviour. Here therefore I have limited myself to only 8 extra comments, intended primarily to stimulate AGARD organisational action and with hopefully a realistic expectation of their practical implementation.

(1) The need for more regular contacts between windtunnel and flight-test personnel still has to be stressed and warrants more joint technical meetings, being aggravated particularly by the increased interaction between performance and flight-handling qualities; while the sophisticated measurement and analysis techniques now employed should be made more compatible between the ground-based and in-flight facilities. Naturally, similar regular exchanges with other theoretical, computer-program and aircraft design personnel have likewise become increasingly important, as well as those between experts in the different disciplines.

(2) In view of the growing usage of system and parameter identification techniques for flight data analysis, a further AGARD review of this topic would now be worthwhile, involving not only relevant experts from flight-test and computer-programing but also windtunnel interests; particularly to clarify the present status in detail, to recommend common definitions and to suggest further practical applications of these techniques.

(3) Wider and better simulation of practical aircraft features at model-scale should be encouraged; especially in respect of propulsors, control aspects including active-control technology, variable-geometry considerations, and in-flight structural deformations with new materials and construction. Moreover, more extensive model mechanisation (powered actuators) and dynamic testing should be supported.

(4) The aerodynamic aspects and research requirements associated with the practical installation and satisfactory release of external stores should be more fully discussed within a joint FDP/FMP Working Group or Symposium; including considerations of extra drag and other installation airloads, local buffeting, aircraft lift and stability effects, store separation trajectories, and associated prediction and measurement techniques.

(5) In-flight scientific investigations on basic fluid mechanics should be more strongly supported, using existing advanced aircraft; e.g. flow transition and separation studies using modern hot-film and laser techniques on a large civil aircraft (e.g. Airbus) and multi-role military aircraft (e.g. Tornado). Complementary windtunnel experiments of course should be planned to take place both before and after the flight tests.

(6) The AGARD FDP Working Group on computational fluid dynamics should be encouraged to extend its valuable work beyond the present year, at least to produce an annual updating of technical capabilities, prospects, implications and recommendations.

(7) The better representation of pilot environment and subjective factors for ground-based and in-flight simulators should be strongly commended, particularly in respect of research on airfield operation and aerial combat conditions.

(8) External noise and internal noise/vibration should be discussed at a suitable FMP meeting , at least in respect of the practical prediction and the cost-effective reduction of possible early-detection and ride-disturbance aspects respectively. More generally, the interaction of reduced detection requirements (radar, infra-red, visual and noise) on aircraft performance/handling and on aircraft design deserves further expert discussion.

REFERENCES
(Symposium Papers - AGARD C.P. 339)

1. Ph.Poisson-Quinton. Conclusions of the FMP Symposium in Valloire (1975) and progress on ground/flight correlation.

2. T.W. Binion, X. Vaucheret & X. Bouis. Progress in windtunnel test techniques and in the corrections and analysis of results.

3A J.K. Hodge, D.R. Audley, P.W. Phillips & E.K. Hertzler. Aerothermodynamic flight envelope expansion for a manned lifting re-entry vehicle (space shuttle).

3B P.W. Kirsten & D.F. Richardson. Predicted and flight test results of the performance and stability and control of the space shuttle from re-entry to landing.

4A D. Jacob, D. Welte & H. Wunnenberg. A comparison between windtunnel and flight results for aerodynamic performance on the Alpha-jet experimental aircraft with a transonic wing.

4B H. Buers, V. Schmitt & J. Lerat. A comparison of the wing pressure distribution and local wake survey from analytical, windtunnel and flight results on the Alpha-jet experimental aircraft with a transonic wing.

5 D.F. Fisher & N.S. Dougherty. Flight and windtunnel correlation of boundary-layer transition on the AEDC transition cone.

6 B. Ewald & W. Burgsmuller. Experimental investigations of transport aircraft low speed engine interference effects and flight test correlation.

7. F. Mavriplis. Comparison of prediction, windtunnel and flight test data for the Canadair Challenger turbofan aircraft.

8. D.C. Leyland. Lessons from Tornado afterbody development.

9. Brief comments on performance correlation:-
A) R.A. Wood - Aircraft.
B) J.W. Britton - Aircraft Store drag. *
C) J.M. Hardy - Propulsive afterbody.

10. P.L. Mathe. Behaviour of a combat aircraft at high incidence: correlation between prediction and flight.

11. G.F. Moss, A.J. Ross, G.F. Edwards & E.B. Jefferies. The use of free-flight models for the prediction of departure control.

12. S.H. Teige, B.S.A. Nilsson, S.J. Boerson & A.N. Kraan. Comparison of flight and windtunnel buffeting measurements on the SAAB 105 aircraft.

13. D.G. Mabey & B.E. Cripps. Some measurements of buffeting on a flutter model of a typical strike aircraft.

14. J.A. Mulder, J.G. den Hollander & H. Binkhorst. Aerodynamic model identification from dynamic flight test data and windtunnel experiments.

15. D.L. Key, R.S. Hansen, W.B. Cleveland & W.Y. Abbott. Helicopter simulation validation using flight data.

16. J. Kaletka & H.J. Langer. Correlation aspects of analytical, windtunnel and flight test results for a hingeless rotor helicopter.

17. Correlation aspects in the identification of dynamic effects using complementary techniques.

17A. K. Wilhelm & R. Verbrugge. Flight in turbulence - gust alleviation
17B. D. Tristrant. Behaviour at high angles

18. L.G. Schroers. Dynamic structural aeroelastic stability testing of the XV-15 tilt-rotor research aircraft.

19A K. Knauer. Ground and flight test techniques used for proof of structural integrity of the Tornado combat aircraft.

19B J.R. Dovey & G. Moretti. Comparison of flight loads measurements results and predictions for Tornado.

19C G. De Ferrari, A Lotze and L. Pyrah. Correlation problems between flutter flight tests data and ground tests/calculation results for a variable sweep wing aircraft.

20. G.B. Gilyard & J.W. Edwards. Real-time flutter analysis of an active flutter-suppression system on a remotely piloted research aircraft.

21. H. Zimmermann & R. Destuynder. Flight flutter testing with emphasis on the tip vane method.

22. F. Porrato & V. Mo. A theoretical/experimental technique to evaluate store separation characteristics.

23. F. Toulmay. Helicopter air inlets: design process, windtunnel testing and correlations with flight data.

24. J. Williams. Synthesis of responses to AGARD-FMP questionnaire on prediction techniques and flight correlation.

* Ref. 9B is not printed in CP 339. Ref 9C is printed as 9B.

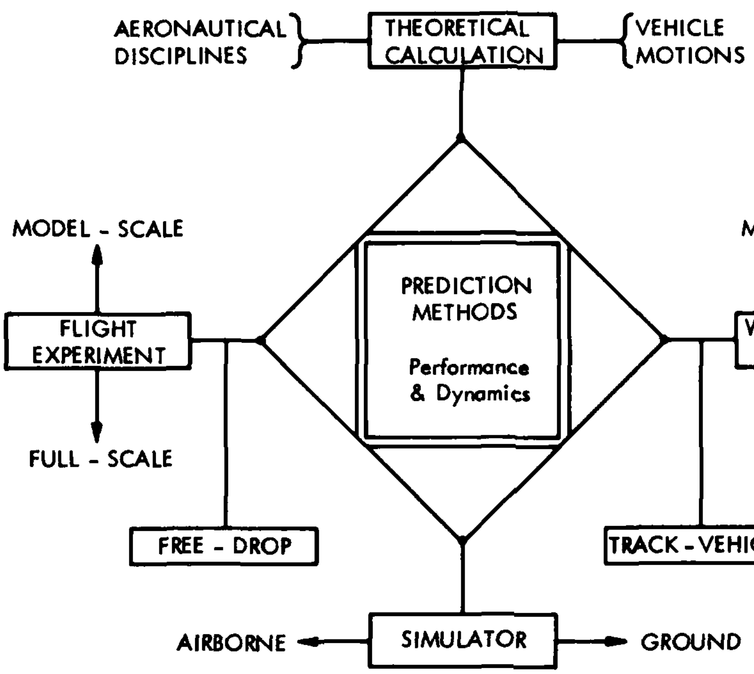


Fig.1 Complementary prediction/design tools

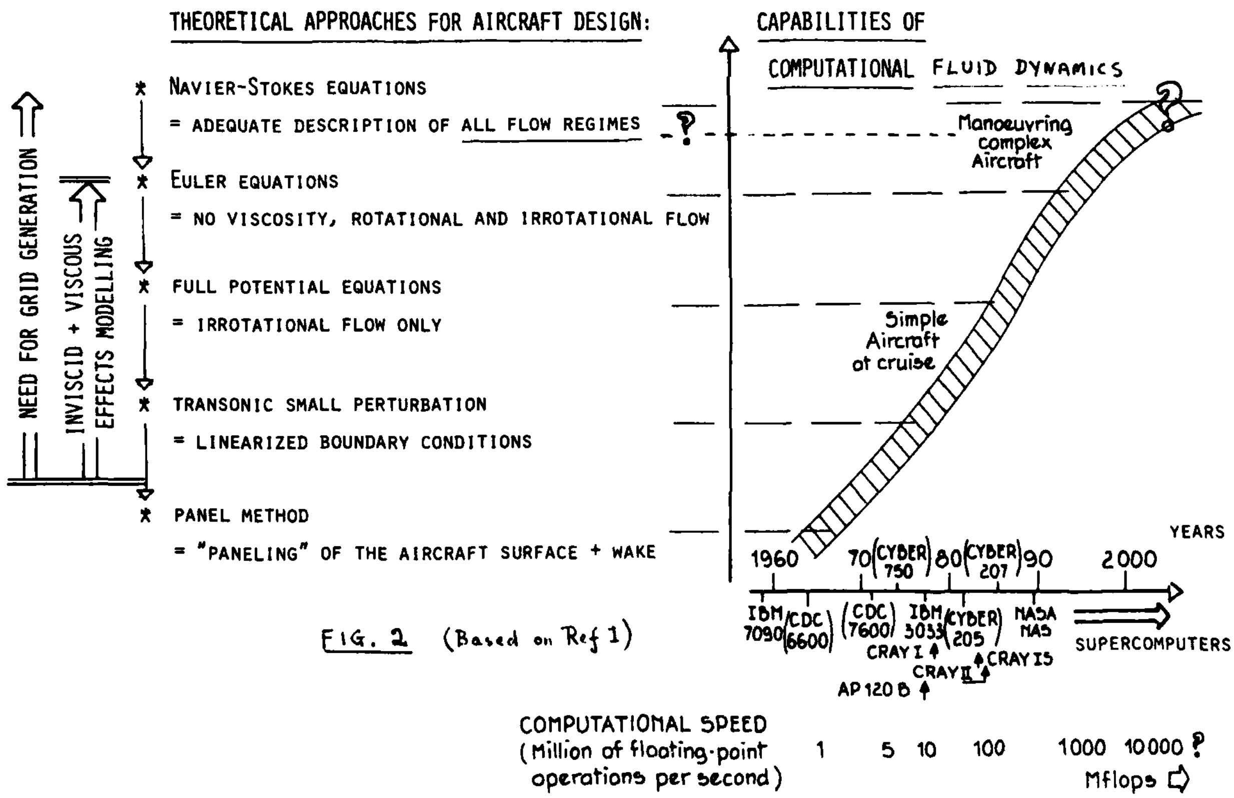


Fig.2 (Based on Ref.1)

REPORT DOCUMENTATION PAGE

1. Recipient's Reference	2. Originator's Reference	3. Further Reference	4. Security Classification of Document
	AGARD-AR-191	ISBN 92-835-1454-8	UNCLASSIFIED

5. Originator	Advisory Group for Aerospace Research and Development North Atlantic Treaty Organization 7 rue Ancelle, 92200 Neuilly sur Seine, France
6. Title	GROUND/FLIGHT TEST TECHNIQUES AND CORRELATION
7. Presented at	

8. Author(s)/Editor(s)	9. Date
John Williams	June 1983

10. Author's/Editor's Address	11. Pages
Aeronautics and Astronautics Department Southampton University Southampton, Hampshire, England	30

12. Distribution Statement	This document is distributed in accordance with AGARD policies and regulations, which are outlined on the Outside Back Covers of all AGARD publications.

13. Keywords/Descriptors

Flight tests
Static tests
Test equipment
Correlation

14. Abstract

This report evaluates the 24 papers and the discussions of the AGARD Flight Mechanics Panel Symposium on "Ground/Flight Test Techniques and Correlation" held 11–14 October 1982 in Cesme (Izmir), Turkey. The Introduction together with the Conclusions and Recommendations offer a brief background and assessment suitable for executive information and action, the remaining detail being concerned with the individual technical topics and the related constructive comments of the Symposium. The full text of the papers is available in the AGARD Conference Proceedings No.339, published Feb. 1983.

This Advisory Report was prepared at the request of the Flight Mechanics Panel of AGARD.

AGARD Advisory Report No.AR 191
Advisory Group for Aerospace Research and Development, NATO
TECHNICAL EVALUATION REPORT OF THE SYMPOSIUM ON "GROUND/FLIGHT TEST TECHNIQUES AND CORRELATION"
by John Williams
Published June 1983
30 pages

This report evaluates the 24 papers and the discussions of the AGARD Flight Mechanics Panel Symposium on "Ground/Flight Test Techniques and Correlation" held 11–14 October 1982 in Cesme (Izmir), Turkey. The Introduction together with the Conclusions and Recommendations offer a brief background and

P.T.O.

AGARD-AR-191

Flight tests
Static tests
Test equipment
Correlation

AGARD Advisory Report No.AR 191
Advisory Group for Aerospace Research and Development, NATO
TECHNICAL EVALUATION REPORT OF THE SYMPOSIUM ON "GROUND/FLIGHT TEST TECHNIQUES AND CORRELATION"
by John Williams
Published June 1983
30 pages

This report evaluates the 24 papers and the discussions of the AGARD Flight Mechanics Panel Symposium on "Ground/Flight Test Techniques and Correlation" held 11–14 October 1982 in Cesme (Izmir), Turkey. The Introduction together with the Conclusions and Recommendations offer a brief background and

P.T.O.

AGARD-AR-191

Flight tests
Static tests
Test equipment
Correlation

AGARD Advisory Report No.AR 191
Advisory Group for Aerospace Research and Development, NATO
TECHNICAL EVALUATION REPORT OF THE SYMPOSIUM ON "GROUND/FLIGHT TEST TECHNIQUES AND CORRELATION"
by John Williams
Published June 1983
30 pages

This report evaluates the 24 papers and the discussions of the AGARD Flight Mechanics Panel Symposium on "Ground/Flight Test Techniques and Correlation" held 11–14 October 1982 in Cesme (Izmir), Turkey. The Introduction together with the Conclusions and Recommendations offer a brief background and

P.T.O.

AGARD-AR-191

Flight tests
Static tests
Test equipment
Correlation

AGARD Advisory Report No.AR 191
Advisory Group for Aerospace Research and Development, NATO
TECHNICAL EVALUATION REPORT OF THE SYMPOSIUM ON "GROUND/FLIGHT TEST TECHNIQUES AND CORRELATION"
by John Williams
Published June 1983
30 pages

This report evaluates the 24 papers and the discussions of the AGARD Flight Mechanics Panel Symposium on "Ground/Flight Test Techniques and Correlation" held 11–14 October 1982 in Cesme (Izmir), Turkey. The Introduction together with the Conclusions and Recommendations offer a brief background and

P.T.O.

AGARD-AR-191

Flight tests
Static tests
Test equipment
Correlation

assessment suitable for executive information and action, the remaining detail being concerned with the individual technical topics and the related constructive comments of the Symposium. The full text of the papers is available in the AGARD Conference Proceedings No.339, published Feb. 1983.

This Advisory Report was prepared at the request of the Flight Mechanics Panel of AGARD.

ISBN 92-835-1454-8

assessment suitable for executive information and action, the remaining detail being concerned with the individual technical topics and the related constructive comments of the Symposium. The full text of the papers is available in the AGARD Conference Proceedings No.339, published Feb. 1983.

This Advisory Report was prepared at the request of the Flight Mechanics Panel of AGARD.

ISBN 92-835-1454-8

assessment suitable for executive information and action, the remaining detail being concerned with the individual technical topics and the related constructive comments of the Symposium. The full text of the papers is available in the AGARD Conference Proceedings No.339, published Feb. 1983.

This Advisory Report was prepared at the request of the Flight Mechanics Panel of AGARD.

ISBN 92-835-1454-8

assessment suitable for executive information and action, the remaining detail being concerned with the individual technical topics and the related constructive comments of the Symposium. The full text of the papers is available in the AGARD Conference Proceedings No.339, published Feb. 1983.

This Advisory Report was prepared at the request of the Flight Mechanics Panel of AGARD.

ISBN 92-835-1454-8

AGARD

NATO OTAN

7 RUE ANCELLE · 92200 NEUILLY-SUR-SEINE

FRANCE

Telephone 745.08.10 · Telex 610176

DISTRIBUTION OF UNCLASSIFIED AGARD PUBLICATIONS

AGARD does NOT hold stocks of AGARD publications at the above address for general distribution. Initial distribution of AGARD publications is made to AGARD Member Nations through the following National Distribution Centres. Further copies are sometimes available from these Centres, but if not may be purchased in Microfiche or Photocopy form from the Purchase Agencies listed below.

NATIONAL DISTRIBUTION CENTRES

BELGIUM
Coordonnateur AGARD VSL
Etat-Major de la Force Aérienne
Quartier Reine Elisabeth
Rue d'Evere, 1140 Bruxelles

CANADA
Defence Science Information Services
Department of National Defence
Ottawa, Ontario K1A OK2

DENMARK
Danish Defence Research Board
Østerbrogades Kaserne
Copenhagen Ø

FRANCE
O.N.E.R.A. (Direction)
29 Avenue de la Division Leclerc
92320 Châtillon sous Bagneux

GERMANY
Fachinformationszentrum Energie,
Physik, Mathematik GmbH
Kernforschungszentrum
D-7514 Eggenstein-Leopoldshafen 2

GREECE
Hellenic Air Force General Staff
Research and Development Directorate
Holargos, Athens

ICELAND
Director of Aviation
c/o Flugrad
Reykjavik

ITALY
Aeronautica Militare
Ufficio del Delegato Nazionale all'AGARD
3, Piazzale Adenauer
Roma/EUR

LUXEMBOURG
See Belgium

NETHERLANDS
Netherlands Delegation to AGARD
National Aerospace Laboratory, NLR
P.O. Box 126
2600 A.C. Delft

NORWAY
Norwegian Defence Research Establishment
Main Library
P.O. Box 25
N-2007 Kjeller

PORTUGAL
Direcção do Serviço de Material
da Forca Aerea
Rua da Escola Politécnica 42
Lisboa
Attn: AGARD National Delegate

TURKEY
Department of Research and Development (ARGE)
Ministry of National Defence, Ankara

UNITED KINGDOM
Defence Research Information Centre
Station Square House
St. Mary Cray
Orpington, Kent BR5 3RE

UNITED STATES
National Aeronautics and Space Administration (NASA)
Langley Field, Virginia 23365
Attn: Report Distribution and Storage Unit

THE UNITED STATES NATIONAL DISTRIBUTION CENTRE (NASA) DOES NOT HOLD STOCKS OF AGARD PUBLICATIONS, AND APPLICATIONS FOR COPIES SHOULD BE MADE DIRECT TO THE NATIONAL TECHNICAL INFORMATION SERVICE (NTIS) AT THE ADDRESS BELOW.

PURCHASE AGENCIES

Microfiche or Photocopy
National Technical
Information Service (NTIS)
5285 Port Royal Road
Springfield
Virginia 22161, USA

Microfiche
Space Documentation Service
European Space Agency
10, rue Mario Nikis
75015 Paris, France

Microfiche or Photocopy
British Library Lending
Division
Boston Spa, Wetherby
West Yorkshire LS23 7BQ
England

Requests for microfiche or photocopies of AGARD documents should include the AGARD serial number, title, author or editor, and publication date. Requests to NTIS should include the NASA accession report number. Full bibliographical references and abstracts of AGARD publications are given in the following journals:

Scientific and Technical Aerospace Reports (STAR)
published by NASA Scientific and Technical
Information Facility
Post Office Box 8757
Baltimore/Washington International Airport
Maryland 21240; USA

Government Reports Announcements (GRA)
published by the National Technical
Information Services, Springfield
Virginia 22161, USA

Printed by Specialised Printing Services Limited
40 Chigwell Lane, Loughton, Essex IG10 3TZ

ISBN 92-835-1454-8

END

FILMED

10-83

DTIC